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FEASIBILITY STUDY OF
LAUNCH VEHICLE GROUND CLOUD NEUTRALIZATION

By

P. C. Vander Arend, S. T. Stoy and T. E. Kranyecz

1 June 1976

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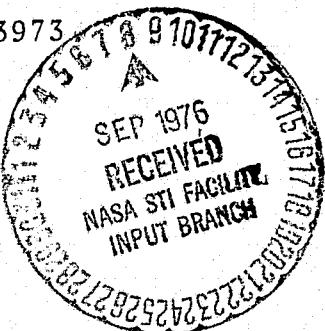
By

CRYOGENIC CONSULTANTS, INC.

Allentown, Pa.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



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FEASIBILITY STUDY
OF
LAUNCH VEHICLE GROUND CLOUD NEUTRALIZATION

By P. C. Vander Arend, S. T. Stoy and T. E. Kranjecz
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SUMMARY

The solid rocket booster engines of the space shuttle will deliver as much as 50,000 kg of hydrogen chloride to the troposphere during the first 24 sec of burning. With the existence of an inversion layer at an altitude of 2-3 km the resulting exhaust cloud with contained hydrogen chloride may remain intact and drift over surrounding territory of the Kennedy Space Center. In case of rain, the hydrogen chloride may be washed out and delivered to the ground in the form of an acid solution.

A relatively large number of chemical agents capable of neutralizing the hydrogen chloride are available as bulk commercial products. These agents may be delivered as a solid, liquid solution or gas to the cloud formed during the initial 24 sec of engine burn. The distribution of hydrogen chloride in the cloud has been analyzed as a function of launch pad geometry and rate of rise of the vehicle during the first 24 sec of burn in order to define neutralization requirements.

Delivery systems of various types have been developed in order to bring the proposed chemical agents in close contact with the hydrogen chloride. Approximately one-third of the total neutralizing agent required can be delivered from a ground installed system at the launch pad; concentrated sodium carbonate solution is the preferred choice of agent for this launch pad system. Two-thirds of the neutralization requirement appears to need delivery by aircraft. Only one chemical agent (ammonia) may be reasonably considered for delivery by aircraft, because weight and bulk of all other agents is too large. Mixing of the neutralizing agents with the contents of the cloud is caused by the strong turbulence present in the cloud shortly after its formation.

A conceptual design of ground installed and airborne delivery systems has been developed. The design lends itself to testing of the concept on a small scale. A cost analysis of these systems has also been made.

INTRODUCTION

During the launch of a space shuttle large quantities of hydrogen chloride are released in the exhaust cloud of the vehicle. The Environmental Statement for the Space Shuttle Program states that operational constraints will be imposed on space shuttle launches to eliminate the possibility of unacceptable hydrogen chloride concentrations in the troposphere. Rain could remove hydrogen chloride from exhaust clouds in concentrations sufficient to have an adverse effect on the surrounding environment during normal launches. Space shuttle launches might even be deferred if weather conditions predicted indicate unacceptably high risk to the surrounding environment. Because the space shuttle traffic model involves a high number of launches per year, careful consideration must be given to the impact of launch constraints on shuttle operations. Potential launch delays due to unacceptable weather conditions are cause for serious concern.

The introduction of chemical agents into the cloud formed by the space shuttle at the time of launch holds out the possibility that the contained hydrogen chloride may be neutralized and rendered harmless to the immediate environment. This study deals with the various chemical agents which may be used to neutralize the cloud and the means by which the chemical agents may be introduced into the cloud.

1. EVALUATION OF POTENTIAL NEUTRALIZING AGENTS

1.1 QUANTITY OF HCl TO BE NEUTRALIZED

It has been assumed that only that part of the exhaust of the rocket which is formed below a potential inversion layer needs to be neutralized. Inversion layers occur at an elevation of 2-3 km. If altitude and mass flow rate from the rocket are known as a function of time, the amount of HCl deposited below the inversion layer may be calculated. The information contained in NASA 33-712 (ref. 1) has been used to determine the quantity of HCl to be neutralized.

It appears that the HCl is deposited into two distinctly separate clouds. These clouds have been defined as the ground cloud formed during the first 8 sec of burn and the column cloud formed during 8-24 sec of burn. Section 3 of this report deals with the formation of these clouds. Quantities of HCl deposited below the inversion layer are then:

- a) 15,600 kg in the ground cloud.
- b) 31,200 kg in the column cloud.

Table I summarizes the components of the exhaust gas and their total quantities in ground cloud and column cloud.

TABLE I
Exhaust Products in Cloud

Component	Weight Fraction	0-8 sec		8-24 sec	
		kg	(lbs)	kg	(lbs)
Al ₂ O ₃	.302	22,541	(49,650)	45,112	(99,366)
HCl	.209	15,622	(34,409)	31,261	(68,857)
CO	.242	18,040	(39,735)	36,106	(79,528)
CO ₂	.034	2,567	(5,654)	5,138	(11,317)
H ₂ O	.094	7,036	(15,498)	14,082	(31,018)
H ₂	.021	1,554	(3,424)	3,110	(6,850)
N ₂	.087	6,531	(14,386)	13,061	(28,768)
Cl	.0029	214	(472)	429	(945)

TABLE I (Continued)

<u>Component</u>	<u>Weight Fraction</u>	0-8 sec		8-24 sec	
		kg	(lbs)	kg	(lbs)
FeCl ₂	.0059	443	(976)	887	(1,953)
*CO ₂	.414	30,911	(68,087)	61,858	(136,252)
*H ₂ O	.282	21,061	(46,391)	42,152	(92,845)

*Exhaust products after afterburn.

1.2 AQUEOUS SOLUTIONS OF NEUTRALIZING AGENTS

Table II lists and summarizes important parameters of five aqueous neutralizing agents. The following should be noted:

- a) Line 4 of Table II assumes that the solution will be stored at 40°C for indefinite lengths of time. However the concentration is that of a saturated solution at 30°C. In the case of ammonium carbonate it is not necessary to store the solution at elevated temperatures.
- b) Line 7 of Table II provides information about the size of tanks required. The size is based on the exact amount required to neutralize 15.6 and 31.2 MT of HCl in ground cloud and column cloud, respectively.
- c) Cost data have been compiled on the basis of verbal quotes by vendors capable of delivering the particular material in bulk quantity to Kennedy Space Center. The cost of mixing and handling at KSC under control of NASA personnel is not included.
- d) Line 8 of Table II provides information about the size of lines and nozzles to be used for injection of the material over a 10 sec period. This period coincides with the time during which the exhaust of the rocket flows through the flame trench.

TABLE I I

Aqueous Solutions of Neutralizing Agents

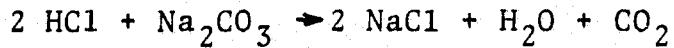
1. Neutralizing Agent:	Sodium Carbonate	Sodium Bicarbonate	Ammonium Carbonate	Ammonia	Ammonium Hydroxide
2. Chemical Formula:	Na_2CO_3	$NaHCO_3$	$(NH_4)_2CO_3 \cdot H_2O$	NH_3	NH_4OH
3. Molecular Weight:	106.0	84.01	114.11	17.003	35.05
4. Solution - Wt. % Neutralizer @ 40°C:	28.6	10.25	50 (@ 20°C)	-	25
5. MT of Solution for:					
a) Ground Cloud:	79.4	252.2	48.84	7.28	29
b) Column Cloud:	158.7	504.4	97.66	14.57	58
6. Density - g per cc @ 40°C:	1.285	1.114	2.00 (Calculated)	0.61	0.905
7. m^3 of Solution to Neutralize:					
a) Ground Cloud:	61.7	226.2	24.4	11.95	32.2
b) Column Cloud:	123.4	452.4	48.8	23.90	64.4
8. Delivery Rate in GPM for 10 Sec in Ground Cloud	9.74×10^4	3.59×10^5	3.87×10^4	1.89×10^4	5.107×10^4
9. Cost per MT of Agent:	\$93.50	\$180.40	\$495 (NASA)	\$187	\$187
10. Cost per Launch for:					
a) Ground Cloud:	\$2,125	\$6,500	\$10,990	\$1,365	\$1,365
b) Column Cloud:	\$4,250	\$13,000	\$21,980	\$2,730	\$2,730
11. Cost per Launch:	\$6,375	\$19,500	\$32,970	\$4,095	\$4,095

1.2.1 Sodium Carbonate (Na_2CO_3)

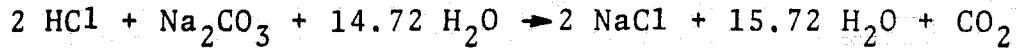
The material is readily available as a commercial product under the name of soda ash. It is shipped in the solid form and its cost in bulk quantity at present is of the order of \$93.50 per MT. Its density in the solid form (white powder) is 2.53 g/cc. However, its bulk density will be less. Figure 1.1 suggests strongly that the solution should be maintained at a temperature somewhat above ambient in order to reduce the bulk quantity of the solution to be injected into the cloud. The solution listed in Table II is the saturation solution at 30-31°C. By maintaining the mixing bath at this temperature a saturated solution may be made. Precipitation of the solid will not occur during the storage period as long as the storage tank is maintained at a temperature above 31°C. Density of the solution is shown in Figure 1.2. The density of the 28.6% solution is extrapolated from this curve.

To neutralize the 15.6 MT of HCl in the ground cloud requires 79.4 MT of solution and injection over a period of 10 sec requires an average flow rate of 97,000 gpm. This flow rate is not excessive and a system for delivery of the Na_2CO_3 solution to the ground cloud is practical. Section 5 of this report deals with the design of the storage and injection system.

The reaction between HCl and Na_2CO_3 is in accordance with the following equation:

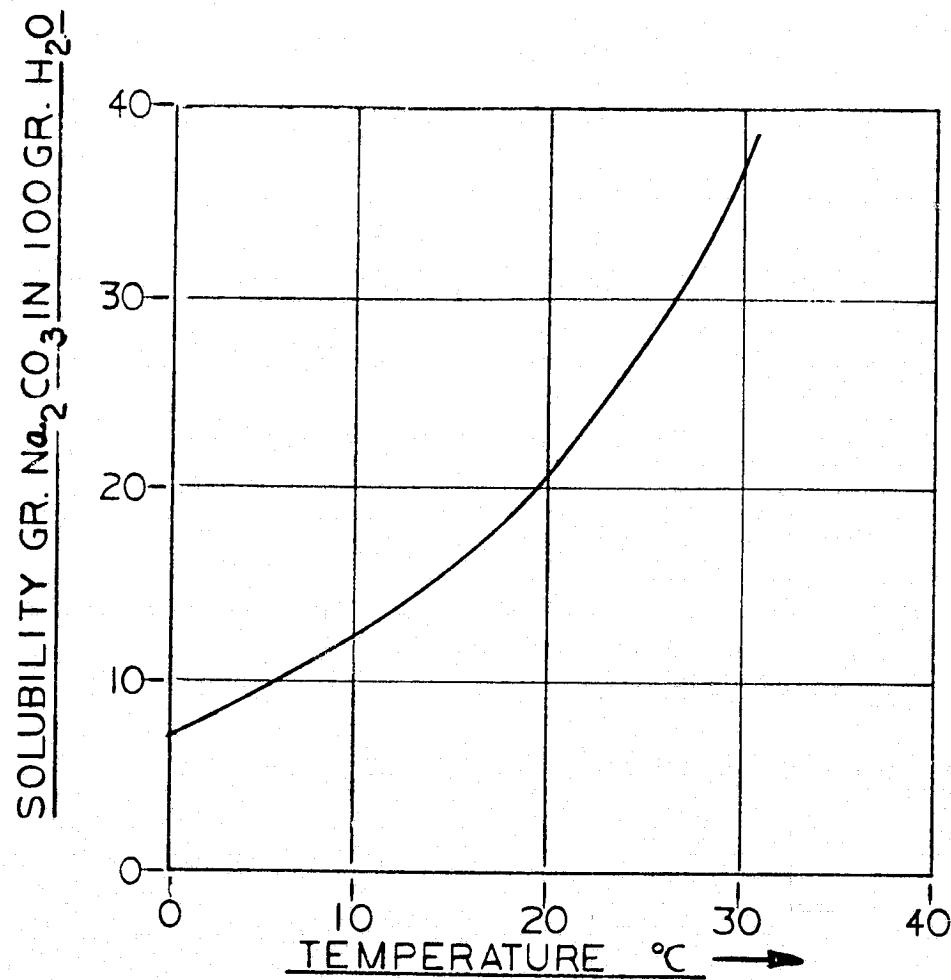


If we carry the water of the initial solution in the equation, it will be as follows:



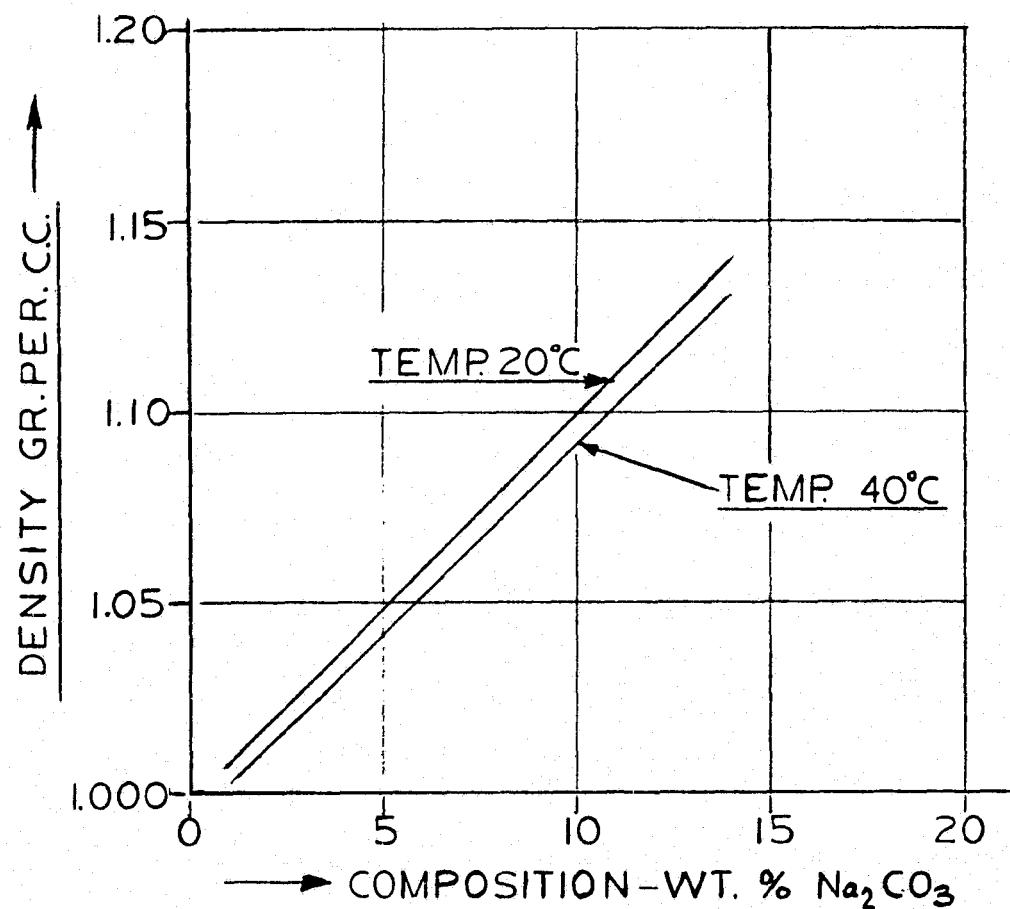
The reaction is exothermic and 83,300 J of heat are released per g mol of HCl. The product of the reaction is a solution of NaCl in water. Figure 1.3 shows the solubility of NaCl in H_2O . The reaction generates a solution of 41 g of NaCl in 100 g of H_2O , and for lack of sufficient water, some NaCl will precipitate as a solid. The addition of 83,300 J per g mol of HCl results in a temperature rise of 60°C of the solution to the boiling point of H_2O plus vaporization of some water.

When the solution is injected in the hot ground cloud, sufficient heat is available to vaporize all of the water of the solution and upon completion of the reaction the ground cloud will contain 25.13 MT of NaCl. This material is in the solid



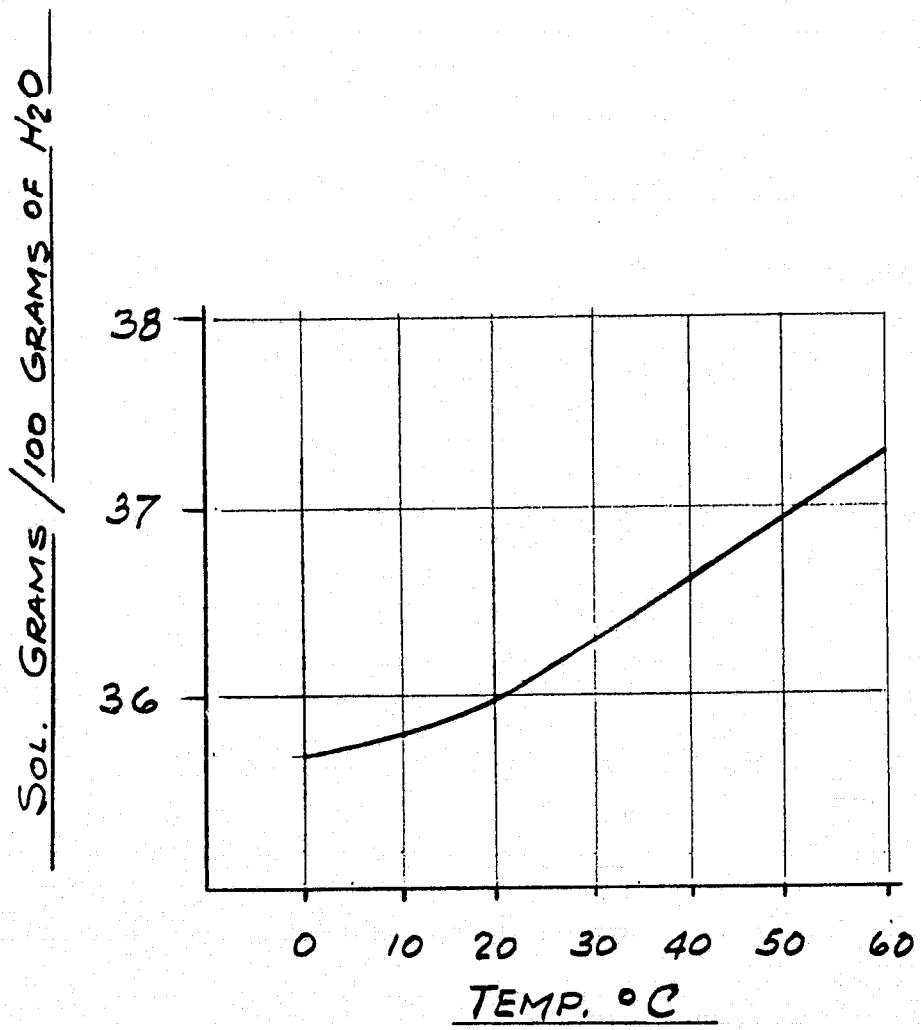
SOLUBILITY OF Na_2CO_3 IN 100CC OF H_2O

FIG.- 1.1



DENSITY OF Na_2CO_3 AQUEOUS SOLUTION

FIG-1.2



SOLUBILITY NaCl IN H_2O

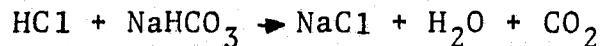
FIGURE 1.3

form, but is hygroscopic and will adsorb water vapor from its environment. The presence of salt in large quantity in the cloud is of some importance to the environment. The salt will be washed out in case of rainfall and the problem on the ground below has changed from one of acid rain to one of salt water rainfall. Section 4 of this report deals with this subject in more detail.

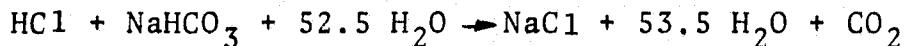
1.2.2 Sodium Bicarbonate (NaHCO_3)

The material is readily available. Its solubility in water is shown in Figure 1.4. By maintaining the storage reservoir at 40°C a solution of 10.25% may be maintained. In order to neutralize the HCl in the ground cloud, 252.3 MT of solution are to be injected. This is more than three times as large as the quantity required for Na_2CO_3 . Volume of 252.3 MT of solution is approximately 226.8 m^3 and flow rates required to inject within 10 sec are of the order of $22.68 \text{ m}^3/\text{sec}$ (360,000 gpm).

The reaction between HCl and NaHCO_3 takes place in accordance with the following equation;



or, with water of solution included, in accordance with:

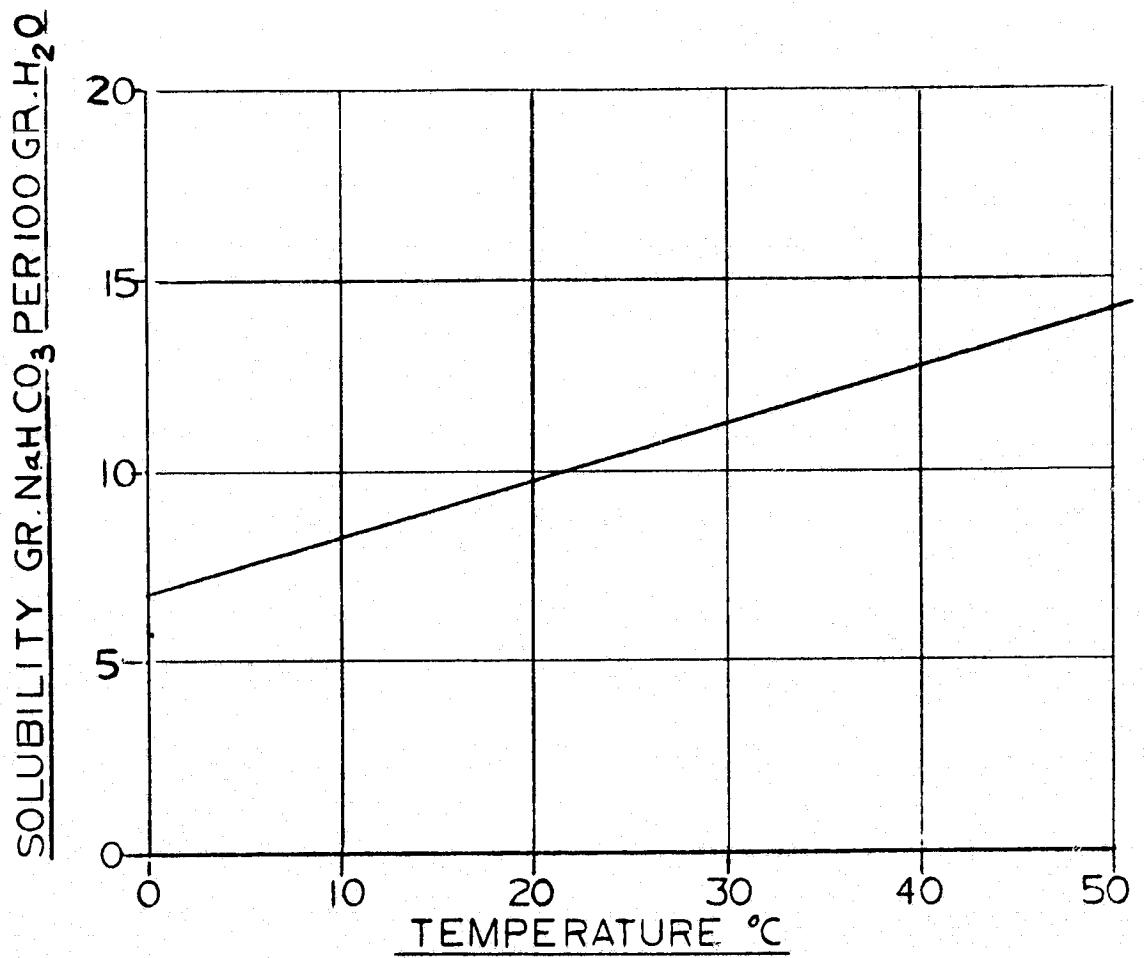


The reaction is exothermic and releases 69,250 J of heat per g mol of HCl neutralized. This heat is distributed over a large amount of solution (NaCl in H_2O). Consequently, the temperature rise of the solution is only some 17°C . All of the NaCl can stay in solution since the concentration is only some 6%.

The results of the injection of the NaHCO_3 solution in the hot ground cloud again leads to the generation of 25.13 MT of salt. Since more water is available, washout by rain probably will be as a more dilute solution than in the case of Na_2CO_3 injection.

1.2.3 Ammonium Carbonate $(\text{NH}_4)_2\text{CO}_3$

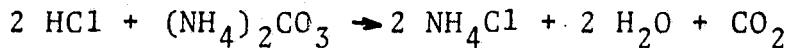
The material is available in bulk quantity. It is extremely soluble in water and at 20°C 100 g of the material will dissolve in 100 g of H_2O . Only 24.57 m^3 of solution



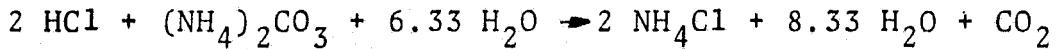
SOLUBILITY OF NaHCO₃ IN 100CC. OF H₂O

FIG.- 1.4

needs to be injected into the ground cloud. The reaction between HCl and $(\text{NH}_4)_2\text{CO}_3$ takes place in accordance with the following equation:



When water of the solution is added, the equation will be:



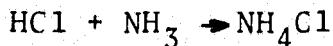
The reaction is exothermic and 94,900 J of heat is released per g mol of HCl. Since the quantity of water participating in the reaction is small, the rise in temperature is large. A considerable part of the ammonium carbonate will dissociate into NH_3 , H_2O and CO_2 . This does not harm the neutralizing reaction. Solubility of NH_4Cl in water at 20°C is 27% (37 g per 100 g). Since 70.6 g are present per 100 g of water, approximately half of the NH_4Cl will settle out as a solid. Total NH_4Cl quantity generated in the ground cloud is 24.7 MT.

1.2.4 Ammonia (NH_3)

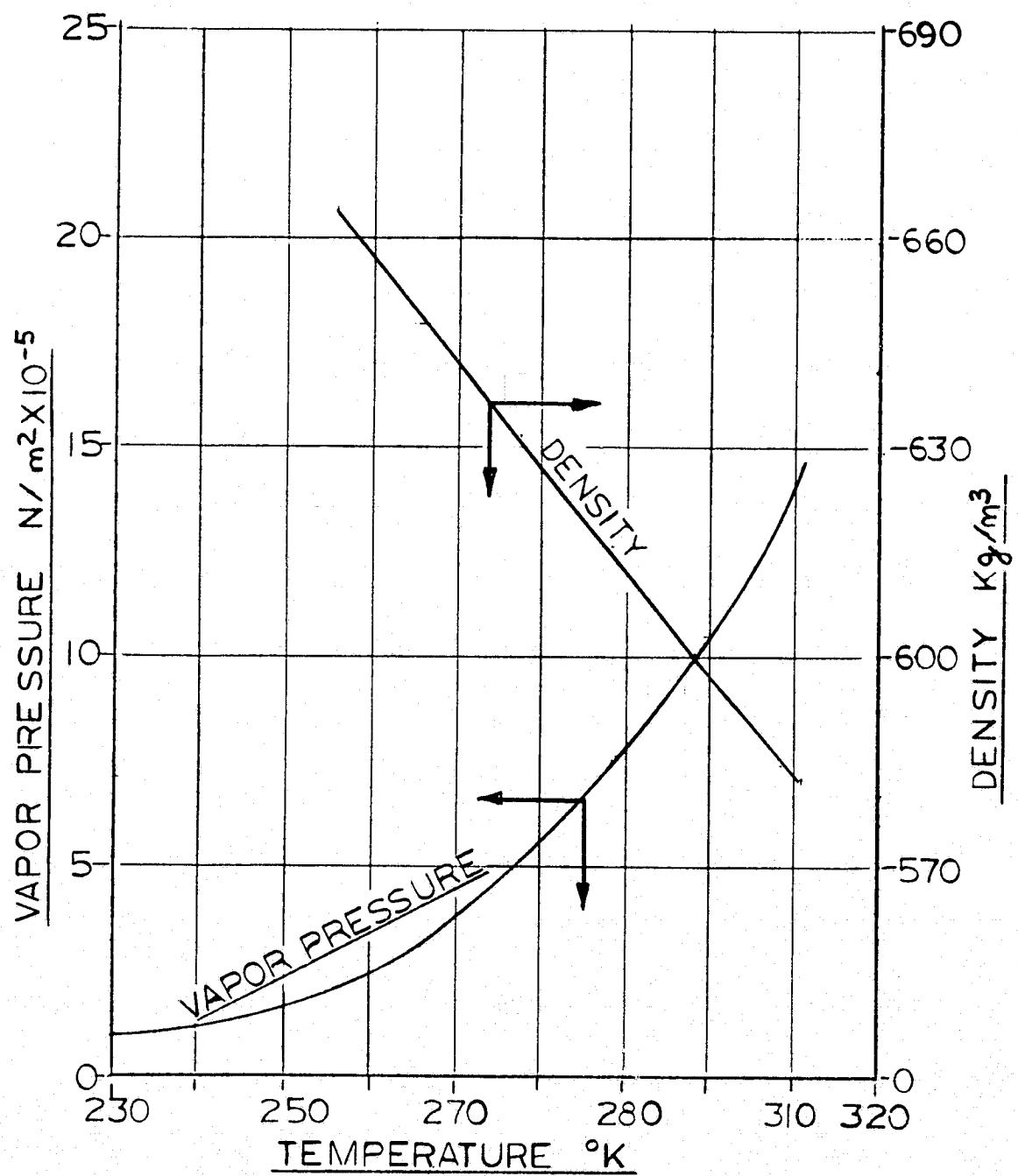
According to the data of Table II NH_3 requires the smallest volume for storage of all neutralizing agents considered. The total quantity required is 21.9 MT of which 7.3 MT is for the ground cloud. NH_3 at ambient temperature is a liquid, if maintained under pressure. Figure 1.5 shows the saturation pressure and density of liquid NH_3 as a function of temperature.

NH_3 requires special handling because of its safety problems. Mixed with air it is flammable within a certain mixture range (Figure 1.6). Although flammable, its ignition temperature is fairly high ($651^\circ\text{C} = 1,204^\circ\text{F}$). The NH_3 vapor is highly toxic and Underwriters Laboratories classifies it in Toxicity Group 2. Ammonia is commercially available in bulk quantity. It is stored, transported and handled as a liquid of ambient temperature and pressure dependent on its temperature.

The reaction between NH_3 and HCl takes place in accordance with the equation:



The reaction is strongly exothermic and releases 105,200 J per g mol of HCl. If the reaction were to take place in the



VAPOR PRESSURE & DENSITY OF LIQUID NH_3

FIG.-1.5

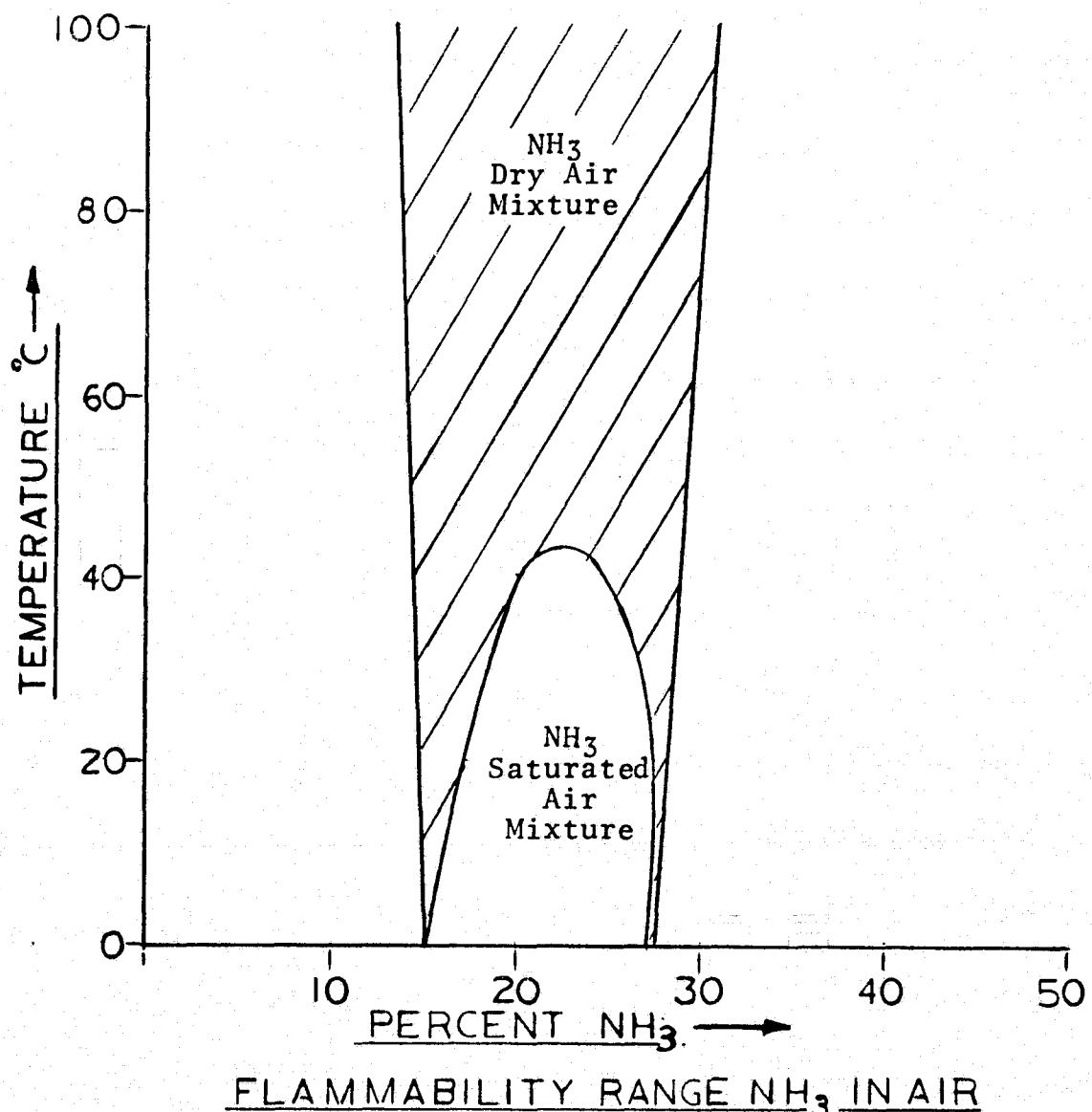


FIG.-1.6

absence of other gases of the ground cloud temperature rise of the product of the reaction would be high. NH_3 cannot be injected in the hot ground cloud, since it will dissociate into N_2 and H_2 . The reaction takes place rather rapidly at temperatures above 400°C.

1.2.5 Ammonium Hydroxide (NH_4OH)

In order to eliminate the safety problems associated with NH_3 , it is possible to make a weak basic solution by dissolving NH_3 in H_2O . At 20°C, 50.15 g of NH_3 will dissolve in 100 g of water. However, the vapor pressure of this mixture is 15 psia at 20°C. It needs to be stored in a closed container to be able to accommodate higher temperatures than 20°C without venting gas. The vented gas would be essentially pure ammonia. By reducing the concentration of NH_3 in the solution to 25% by weight, vapor pressure is reduced to well below 1 atmosphere even at 38°C. Long time storage in a container at atmospheric pressure may be achieved without venting NH_3 from the container. Figure 1.7 shows the percent of NH_3 (by weight) in H_2O as a function of temperature with a vapor pressure of 1 atm (line 1). Line 2 is the composition of the vapor in equilibrium with the liquid. By maintaining a concentration of the solution well below line 1, the total vapor pressure of the mixture is below 1 atm and leakage of NH_3 from the tank is minimal. Fig. 1.6 shows that for a mixture of ammonia and wet air the limits of flammability are narrowed rapidly until they meet at approximately 44°C. The addition of water vapor to the mixture is sufficient to make it nonflammable.

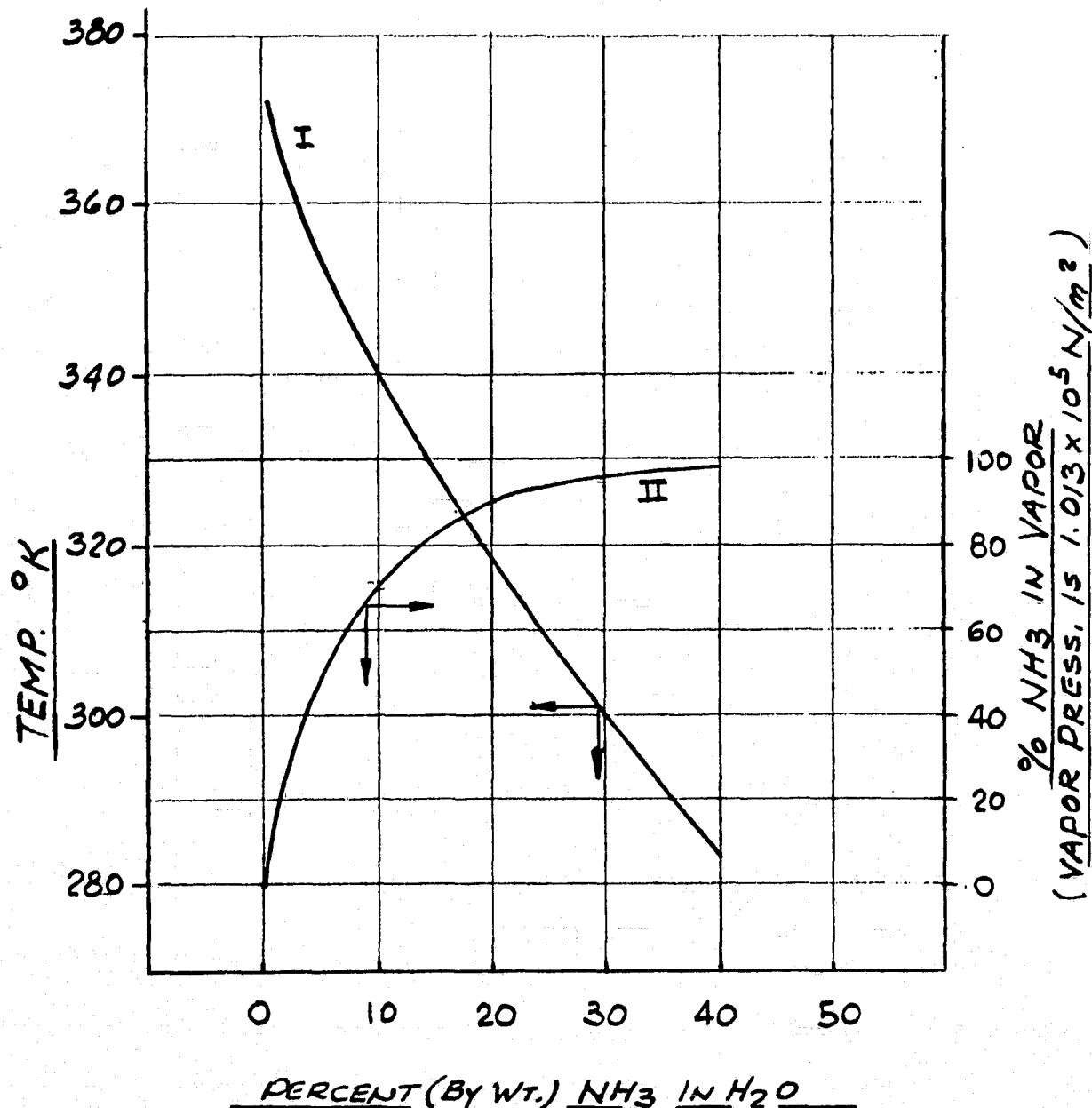
The total quantity to be injected for neutralization of the ground cloud is still relatively small and equipment to handle the solution on the ground is small in size. The neutralizing reaction is exothermic and takes place in accordance with:



Rate of heat release is 142,000 J per g mol of HCl.

1.2.6 Effect of Exothermic Reaction on the Buoyancy of the Ground Cloud

All soluble neutralizing agents of Table II generate heat during the neutralizing reaction. Table III shows the total quantity released when 15.6 MT of HCl is neutralized. The



PARTIAL PRESSURE OF NH_3 AND TOTAL VAPOR PRESSURE OF AQUEOUS SOLUTIONS OF NH_3

FIGURE 1.7

amounts of heat released during afterburning of H_2 and CO in the exhaust cloud are larger by an order of magnitude. For this reason, it does not appear that the temperature effect of the neutralizing reaction is a large one. For instance, the ground cloud has a volume of $8.8 \times 10^6 \text{ m}^3$ ($3.1 \times 10^8 \text{ cft}$) if mixing of air and the exhaust has proceeded to a $HC1$ concentration level of 500 ppm. The addition of $3 \times 10^{10} \text{ J}$ of heat to this cloud results in a temperature rise of 3.5°C .

T A B L E I I I

Heat Released during Neutralization of 15.6 MT of $HC1$

<u>Agent</u>	<u>HEAT RELEASED</u>	
	<u>Joules</u>	<u>(Btu)</u>
Na_2CO_3	3.57×10^{10}	(3.38×10^7)
$NaHCO_3$	2.96×10^{10}	(2.81×10^7)
$(NH_4)_2CO_3$	3.01×10^{10}	(2.85×10^7)
NH_3	1.99×10^{10}	(1.89×10^7)
NH_4OH	1.53×10^{10}	(1.45×10^7)

1.3 SOLID NEUTRALIZING AGENTS

Table IV lists and summarizes three solid neutralizing agents. The following should be noted:

- The material will be stored in the powder form. Particle size is 150 microns, when procured from commercial suppliers at the prices listed under line 8. The material may be made available with smaller particle size at increased costs.

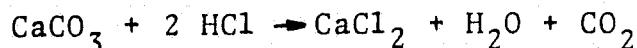
1.3.1 Calcium Carbonate ($CaCO_3$)

The material is readily available under the name of limestone. It is shipped in bulk quantity as a powder. Normal commercial practice results in grinding to a particle size, such that 98% of the material is smaller than 100 mesh (150 micron particle size).

To neutralize the ground cloud requires 21.4 MT. With a density of 1.6 g/cc the volume required is 13.4 m^3 . The reaction takes place in accordance with:

T A B L E I V
Solid Neutralizing Agents

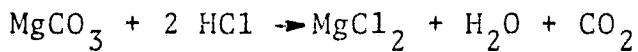
1. Neutralizing Agent:	Calcium Carbonate (Limestone)	Magnesium Carbonate	Dolomite Calcium Magnesium Carbonate	
2. Chemical Formula:	CaCO_3	MgCO_3	$\text{CaCO}_3 \cdot \text{MgCO}_3$	
3. Molecular Wt.:	100	84.32	184.41	
4. MT of Solid for:				
a) Ground Cloud:	21.4	17.7	19.5	
b) Column Cloud:	42.8	35.4	39.0	
5. Density - g per cc @ 40°C:	1.60 (Assumed)	1.60 (Assumed)	1.60 (Assumed)	
6. Vol. of Solid to Neutralize:				
a) Ground Cloud:	13.4 m^3	11.1 m^3	12.2 m^3	
b) Column Cloud:	26.8 m^3	22.2 m^3	24.4 m^3	
7. Delivery Rate for 10 Sec in Ground Cloud:		$1.34 \text{ m}^3/\text{sec}$	$1.11 \text{ m}^3/\text{sec}$	$1.22 \text{ m}^3/\text{sec}$
8. Cost per MT of Agent:	\$18.43	\$1,650	\$50.50	
9. Cost per Launch for Ground Cloud:	\$395	\$9,800	\$1,000	
10. Cost per Launch for Column Cloud:	\$790	\$19,600	\$2,000	



The reaction is endothermic and 40,500 J are removed per mol of HCl neutralized. The effect of the endothermic reaction on the temperature of the cloud is small compared to that of the afterburning of hydrogen and carbon monoxide. The products of the reaction are solid CaCl_2 , gaseous CO_2 and H_2O . The water will be in the form of liquid or vapor dependent on the temperature of the cloud.

1.3.2 Magnesium Carbonate ($MgCO_3$)

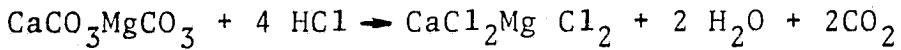
This material is not readily available and needs to be produced in the plant by chemical processes. The neutralizing reaction takes place in accordance with:



The reaction is endothermic and 149,000 J are removed per mol of HCl neutralized. The effect on the temperature of the cloud is rather large relative to that of $CaCO_3$, but still small compared to that of afterburning of hydrogen and carbon monoxide.

1.3.3 Calcium Magnesium Carbonate

The material is readily available under the name of dolomite. It is ground to a fineness of 150 micron size particles. The neutralizing reaction takes place in accordance with:



2. EXHAUST CLOUD FORMATION

2.1 DEFINITION OF THE CLOUD

For the purpose of this study it is necessary to define the cloud which presents a hazard to the environment of the launch facility. Once the cloud has been defined the quantity of HCl present in this cloud is known and this information then leads to the definition of the minimum quantity of neutralizing agent required to neutralize the cloud.

2.1.1 Ground Cloud

After ignition, exhaust gases are directed through the flame trench along a horizontal path away from the launch vehicle. The high velocity of the exhaust gas prevents an immediate rising of this gas in the near vicinity of the vehicle. Photographs and movies indicate that the horizontal velocity slows down sufficiently to realize a vertical ascent of the gas at a distance of 180-240 m from the launch vehicle. At a distance up to 60 m from the launch vehicle most of the gas travels through the flame trench. Afterburning, resulting in a consumption of H_2 and CO, takes place in the interface between exhaust gas and air above and downstream of the flame trench. As a result, the exhaust gas does not cool while traversing through the flame trench.

Afterburning taking place at the rate at which H_2 and CO are generated requires an air flow rate of some 13,600 kg/sec. Actual volume which needs to penetrate into the exhaust flowing through the flame trench results in rather modest air velocities of 10 m/sec at the interface between exhaust and air above the flame trench. Obviously, it is not a problem to mix sufficient air into the exhaust stream flowing through the flame trench, in spite of the flow restriction imposed by the flame trench. The actual rate of air injection into the exhaust gas of the plume will be considerably larger than the minimum required for afterburning. It is of interest to determine the following:

- a) Temperature decay and velocity of the gas as a function of distance traveled along the ground.
- b) Rate of air injection and rate of rise of the ground cloud off the ground.

Temperature of the ground cloud is important because some neutralizing agents cannot tolerate high temperatures and injection at a point too close to the flame trench exit would result in destruction of the agent (e.g., NH₃) rather than neutralization. Velocity is important because the rate of rise of the cloud is determined by its buoyancy. The vertical velocity component due to the density difference between the hot cloud and the environment is rather small and the point of injection of neutralizing agent into the cloud may be chosen along a fairly long path downstream of the flame trench.

Rate of air injection from the environment determines how fast the cloud cools; its buoyancy decreases and its volume increases. The direction of air injection is important because the air injected into the cloud may be used as a carrier for the neutralizing agent. For instance, consider a hot column or ball of gas of a height of 100 m. If the temperature of this gas is 600°K, the weight of this column of gas is approximately half of that of the ambient temperature environment. Pressure differential at the base of this column is then of the order of .15 psig. This pressure differential induces air flow and, if the differential is taken up by one velocity head, velocity will be of the order of 40 m per sec. With a column diameter of 100 m, air flow through the bottom 15 m of column will be at a rate of 213,500 kg/sec.

This example illustrates the events occurring around a large fire and explains the so-called fire storm. These storms are experienced in forest fires and were reported during the war when large parts of a city were on fire.

The presence of a fire storm during the time that hot exhaust gas is added to the ground cloud will generate a flow of air from all directions into the hot cloud. If this is true, neutralizing agent may be injected into the cloud from the periphery of the cloud and it is not absolutely necessary to arrange the equipment in a line extending from the flame trench directly in the path of the hot gas. Figure 2.1 shows the projected 600°K temperature line of the exhaust plume projected on the plan view of the flame trench and downstream area. This projection is obtained from information provided in Figures 2.4 and 2.5 and additional information supplied by NASA, Langley on the temperature profile of the plume as a function of distance downstream from the nozzle.

Since two engines operate in parallel, the 600°K boundary has been pushed out to accommodate the extra gas. Figure 2.1 should be considered as a very rough indication only. However, it shows that we may anticipate a band of 60-90 m width inside of which the hot gas is contained. Figure 2.2

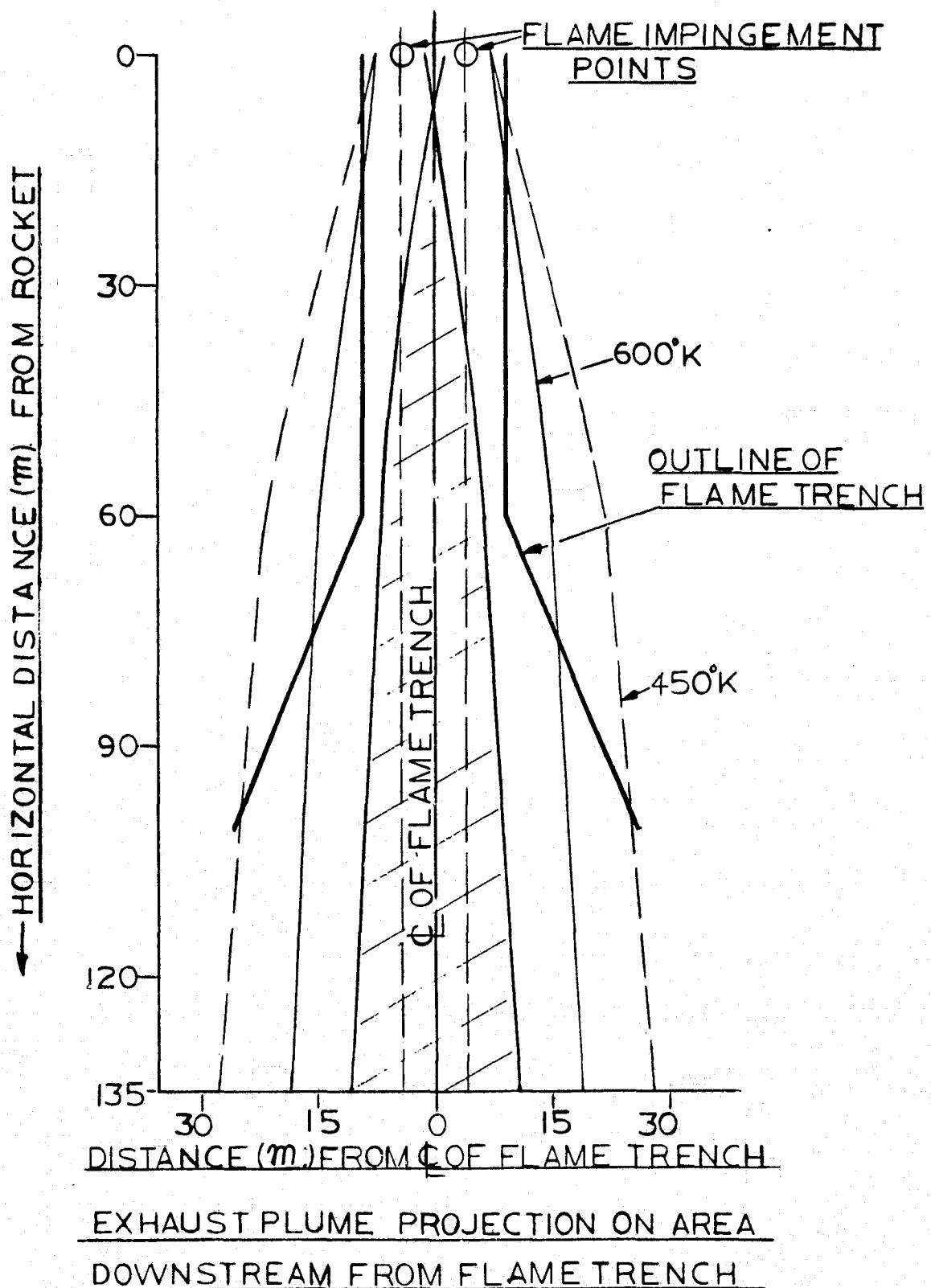
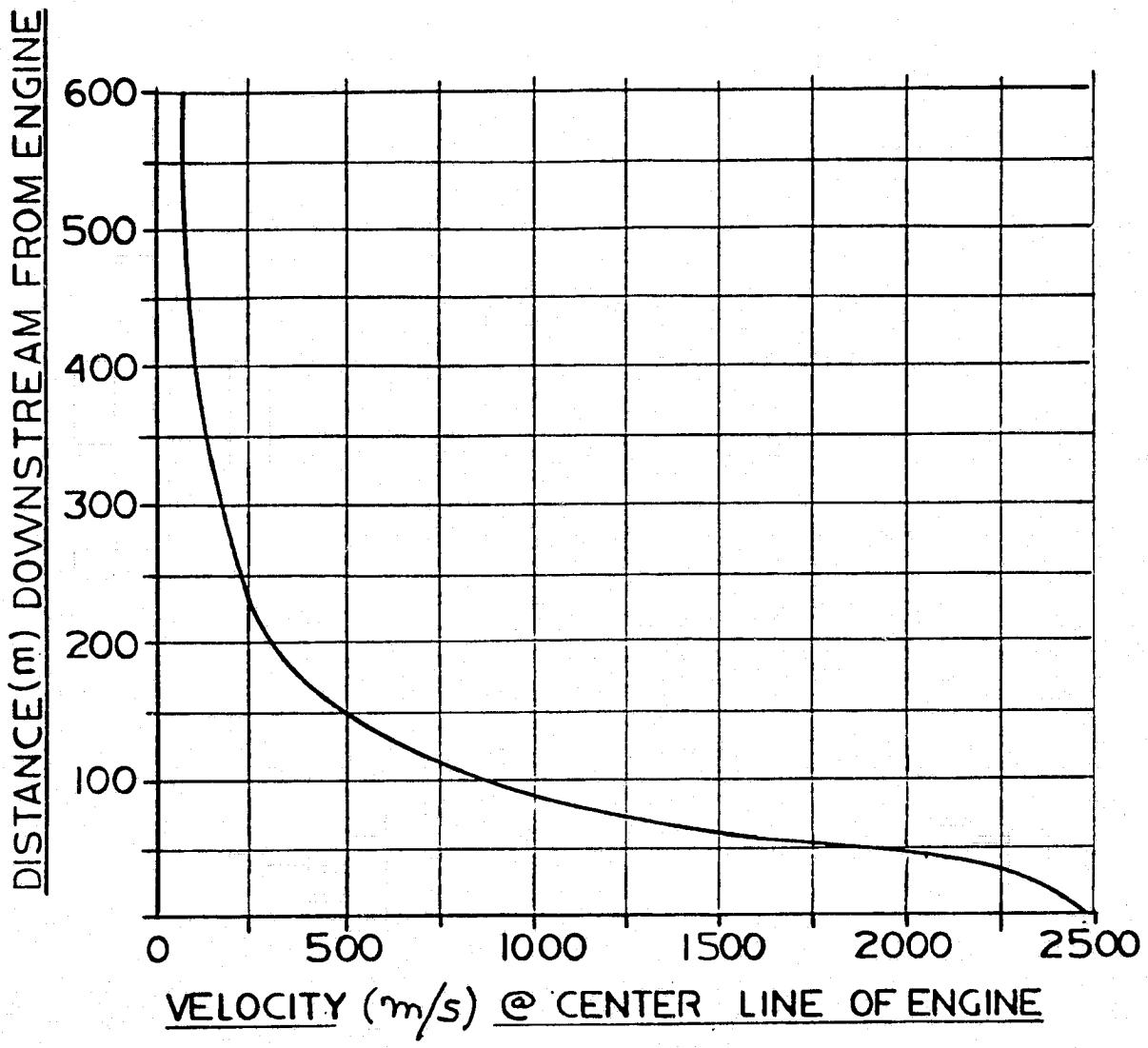


FIG-21



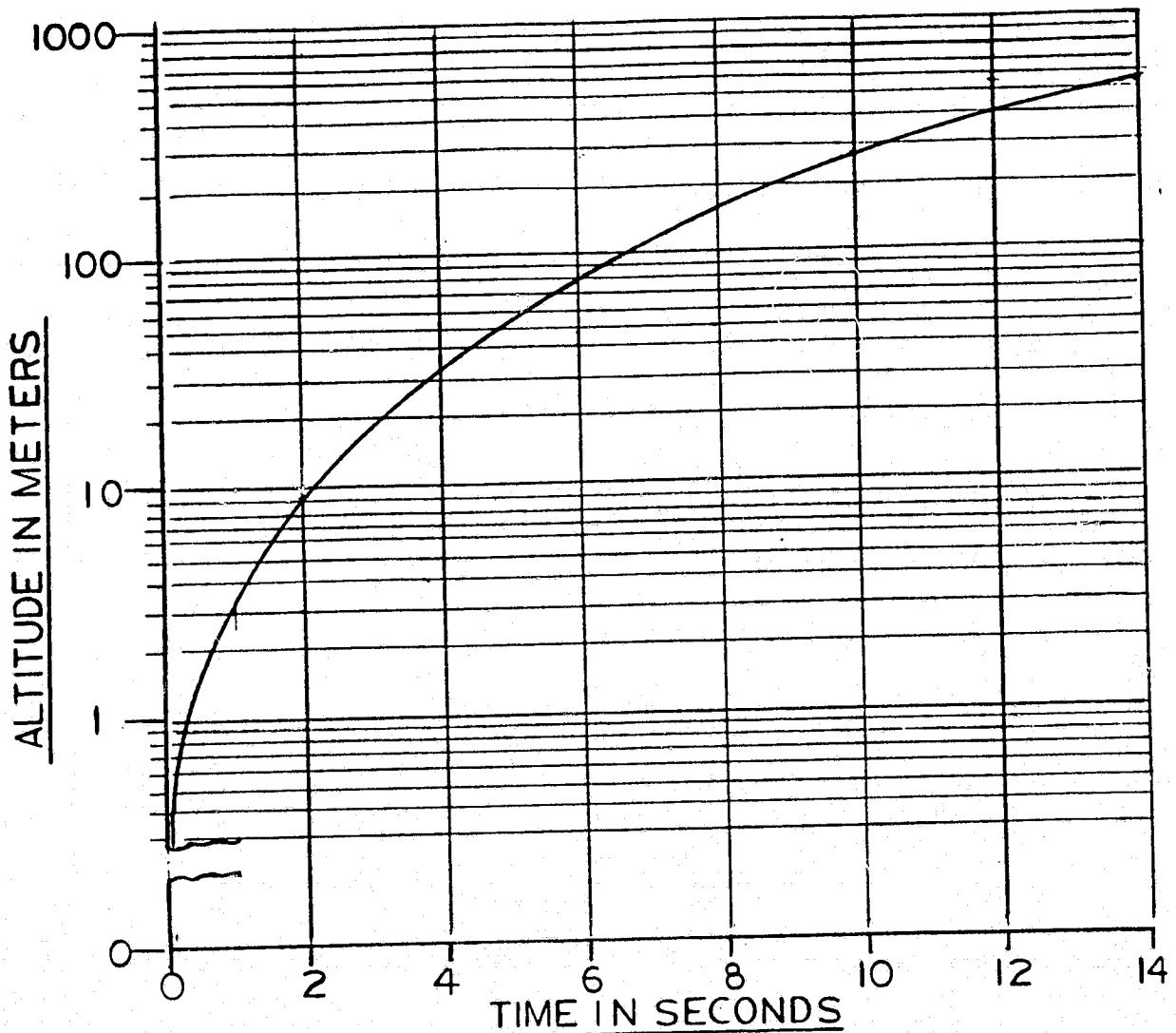
VELOCITY OF EXHAUST GASES FROM SRM

FIG. 2.2

shows the velocity of the exhaust gas downstream of the nozzle (in free flight). The gas flowing through the trench is constrained by some impedances which will slow the velocity down over a distance of less than 600 m (Figure 2.2). The major impedance is the flame deflector which forces a change of direction of 90°. A large fraction of a velocity head is used up in negotiating the turn and this may slow the velocity by a factor of two. Considering Figure 2.2, the point where velocity at the center line of the nozzle is 75 m/sec would move from 570 to 480 m from the position of the launch vehicle. The change is not dramatic.

Pressure drop in the flame trench turns out to be quite small. This is verified by pictures of the launch of Saturn vehicles which show that the flame trench contains the exhaust gas reasonably well. The quantity of exhaust gas contained in the ground cloud is that gas ejected in a period of 6-10 sec after ignition of the solid fuel engines. This time period is determined from information presented in ref. 1 (Technical Memorandum No. 33-712, "Jet Propulsion Laboratory", Feb. 1, 1975) which shows the location of the vehicle above the launch pad as a function of time (Figure 2.3). Since exhaust velocities are at least two orders of magnitude higher than the vehicle velocity, exhaust gas flows through the flame trench and is directed away horizontally to form the so-called ground cloud for a period of 6-10 sec after ignition. For instance, at 6 sec the vehicle is approximately 100 m above the flame trench. The exhaust gas velocity at a point 100 m downstream of the vehicle is of the order of 960 m/sec (Figure 2.2). Clearly, the exhaust gas reaches the ground in a period of less than .1 sec. The width of the flame front increases due to mixing of air and afterburning.

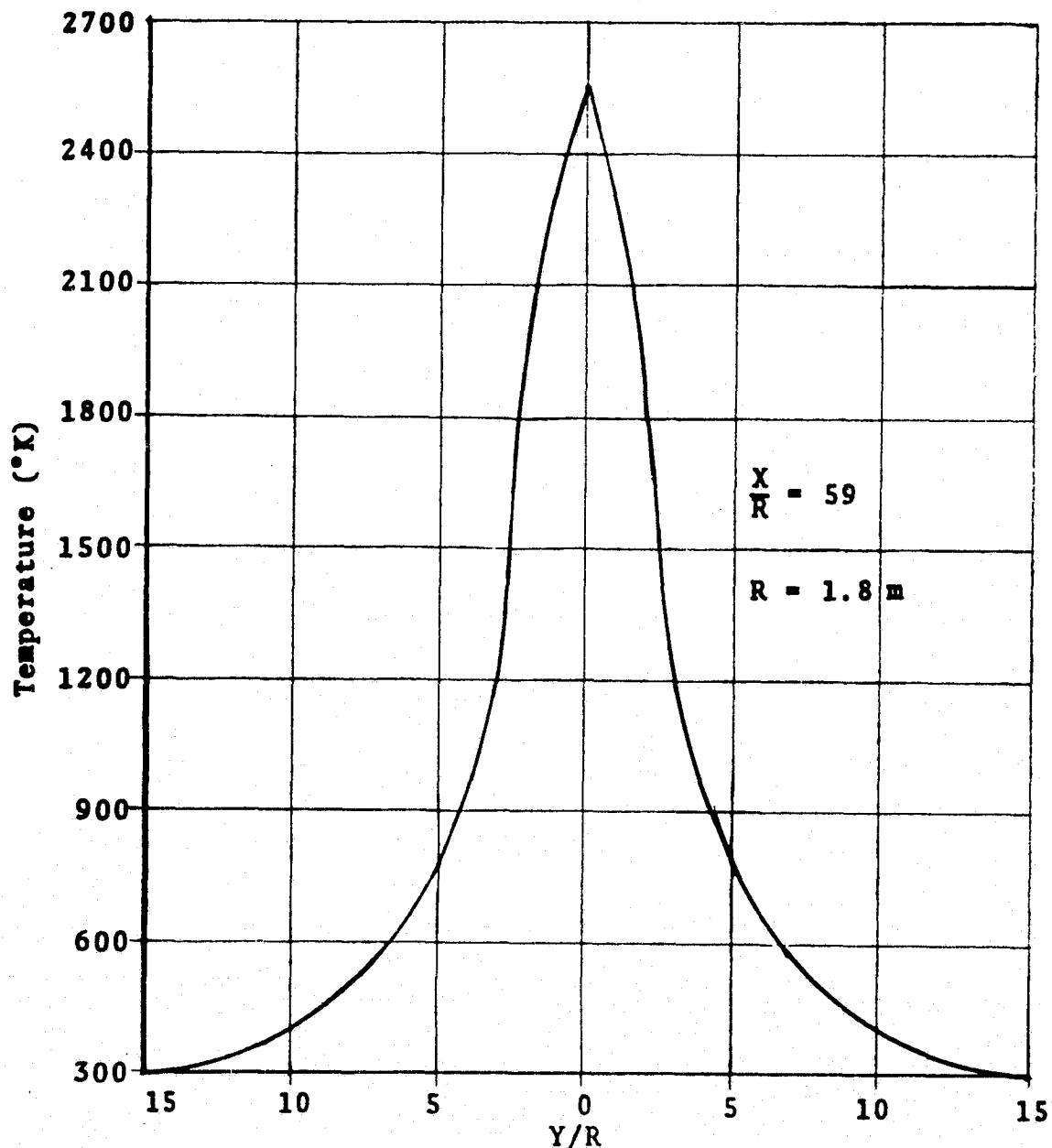
Figure 2.4 shows (at 108 m downstream from the engine) the profile of the exhaust plume (data supplied by G. Pellett of NASA, Langley). It shows that not all of the exhaust gas travels through the flame trench and that some of the exhaust gas impinges on the flat area of the launch platform. This gas will then scatter in all directions. With time the area of impingement increases in diameter, the gas velocity at impingement decreases and less and less gas is directed away in a horizontal direction parallel with the flame trench. On the basis of the information presented above it appears reasonable to define the ground cloud to consist of the products of combustion over a period of approximately 8 sec after ignition takes place. The cloud is formed at a distance of some 200 m from the launch point and contains some 15,600 kg of HC1.



ALTITUDE AS A FUNCTION OF TIME

FIG.-2.3

R is radius of engine at widest point.
X is distance downstream from engine.
Y is ordinate perpendicular to X.



TEMPERATURE PROFILE OF EXHAUST PLUME

FIGURE 2.4

2.1.2 Column Cloud

At 12 sec after launch the vehicle is at an altitude of 360 m above the launch pad and has reached a velocity of 60 m/sec. Downstream of the vehicle the plume extends down to the ground. However, velocity of the exhaust gas at the ground is only some 130 m/sec. Therefore, at about this time the tail end of the plume will leave the ground and will travel upward at the same velocity as the vehicle. At 22 sec into the flight altitude of the vehicle is some 1,300 m and the plume extends for a distance of approximately 600 m downstream of the vehicle.

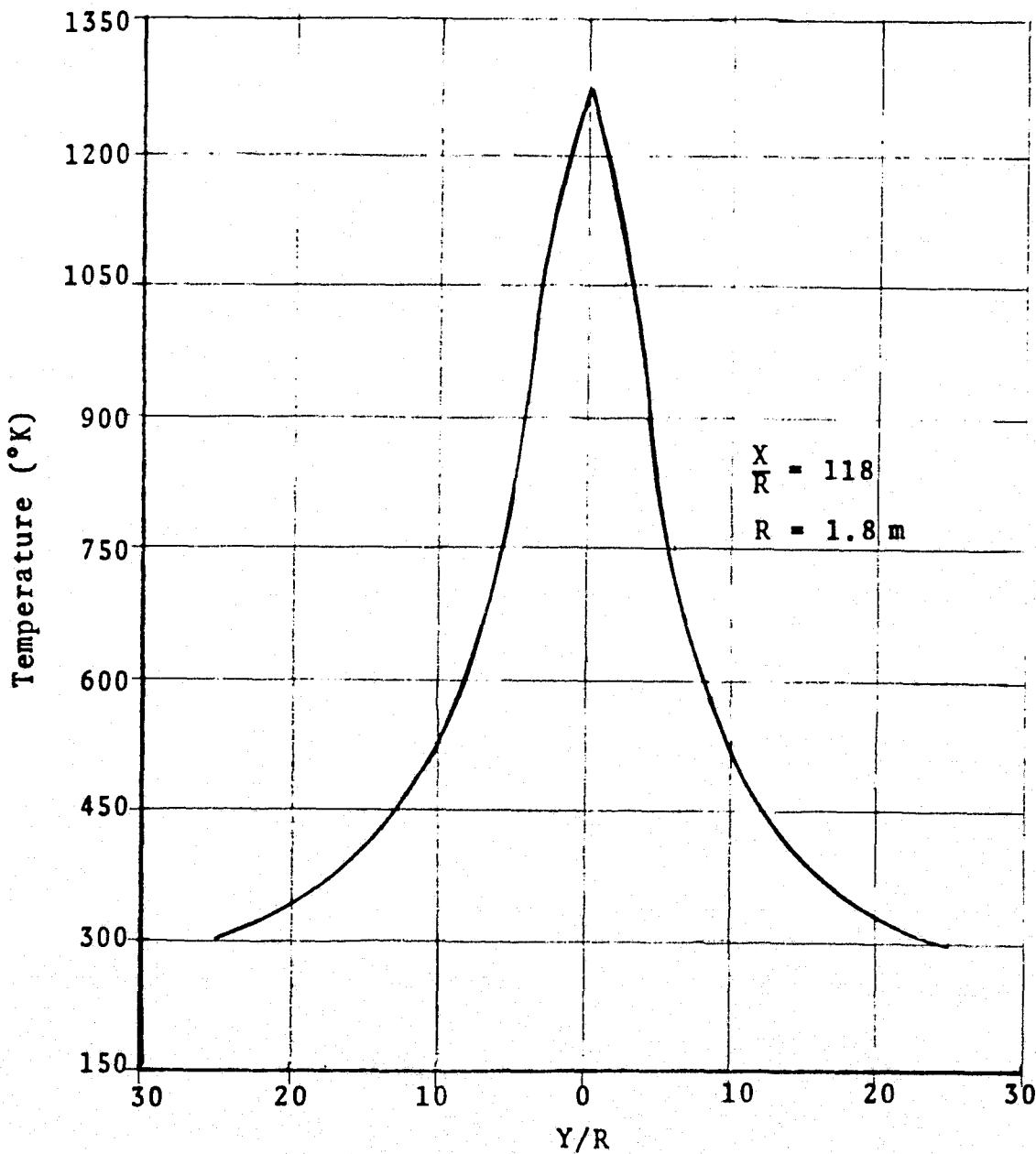
Figure 2.5 gives an indication of the diameter of the plume at a point 200 m downstream. The diameter is roughly 30 engine diameters or of the order of 100 m. Therefore, the vertical cloud which reaches from ground level to 600-900 m altitude will be essentially a vertical column of some 150-180 m in diameter. This cloud contains the combustion products of approximately 16 sec of combustion or 31,000 kg of HC1.

2.1.3 Final Cloud

Both ground cloud and column cloud are buoyant and will rise. At the same time wind will carry the clouds in a horizontal direction. If there is an inversion layer, ground cloud and column cloud will reach this layer and then drift in horizontal direction under the influence of local atmospheric conditions. The time required for ground cloud and various parts of the column cloud to reach the inversion layer is a function of vertical velocity and distance to inversion layer. The ground cloud may as a first approximation be considered to be a sphere traveling at a constant vertical speed. Ref. 2 ("Preliminary Report of the Launch Vehicle Effluent Monitoring Program during the May 20, 1975 Titan III Air Force 777 Launch at KSC") indicates that the vertical velocity of the cloud is of the order of 5 m/sec between 0 and 1.2 km (4,000 ft) altitude and approximately half that speed at higher altitudes. Time to reach the inversion layer is from 240-600 sec.

If we assume that parts of the column cloud move at the same vertical velocity as the ground cloud, then these parts will reach the inversion layer at different times and different locations. The length and width over which the column cloud will be spread out is a function of variations in wind velocity and direction as a function of altitude. Figure 7 of ref. 2 shows a wind speed of approximately 3.5 m/sec between 0 and 1.6 km altitude. Therefore, that part of the column cloud initially located closest to the ground will in 240 sec drift some 800-900 m in horizontal direction, but not in a straight line.

R is radius of engine at widest point.
X is distance downstream from engine.
Y is ordinate perpendicular to X.



TEMPERATURE PROFILE OF EXHAUST PLUME

FIGURE 2.5

Using Figure 7 of ref. 2 as a basis, various parts of the column cloud will arrive at the inversion layer as shown in Figure 2.6. Figure 2.6 shows three sections of the ground cloud and their projected travel path. Curve 1 is that part of the column cloud which starts at ground level. This part of the cloud sees varying wind directions at various elevations and follows a path along line 1. Curve 2 is the section of the column cloud which starts at an elevation of 600 m. It arrives at the inversion layer sooner than the gas of Curve 1 and follows a straight line as soon as it reaches the inversion layer. Line 3 represents the gas which initially is located at the inversion layer. It travels in a straight line.

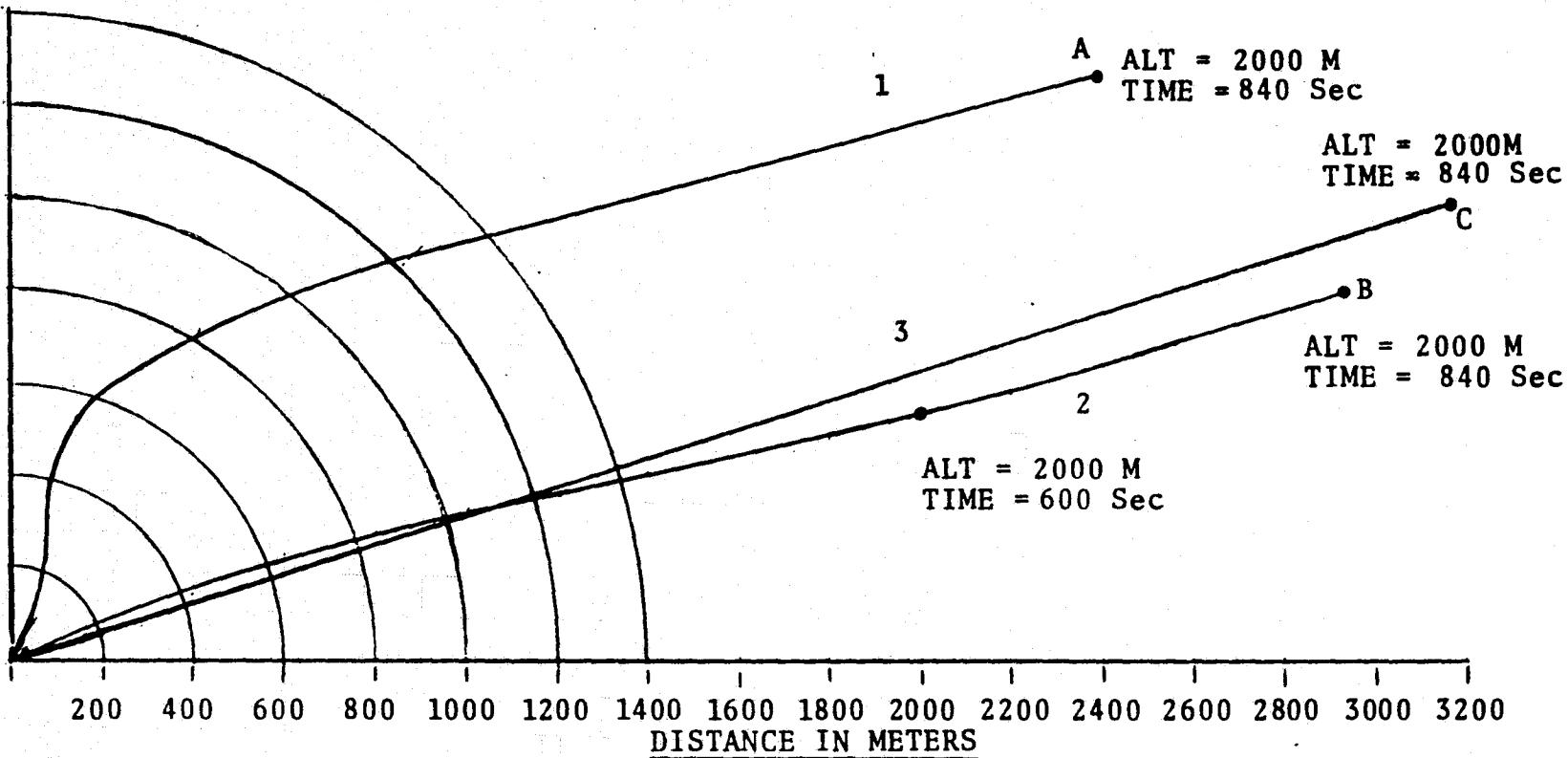
Since wind velocity as a function of altitude was nearly constant for the particular launch on May 20, 1975, points A, B and C will have traveled approximately the same distance in horizontal direction at the time when all of the column cloud has arrived at the inversion layer. If wind velocities had varied greatly as a function of altitude, various parts of the column cloud would travel greatly different distances and the cloud at the inversion layer would show a much larger plan view section. The ground cloud will travel a path similar to that of the column cloud section at ground level. However, there will be a distance of 100-300 m between the bulk of the ground cloud and the column cloud. Generally speaking, the final cloud which travels in a horizontal direction at the inversion layer will have a plan section as shown in Figure 2.6. This section is based on the particular wind conditions of May 20, 1975.

2.2 CONCENTRATION OF HCl IN THE CLOUD

It is assumed that during the initial formation of the ground cloud and column cloud distribution of HCl in these clouds is uniform. This appears reasonable, since HCl will be emitted from the engines at a constant rate and the process of mixing of exhaust products with air is not influenced by launch vehicle velocity at the low elevations under consideration. The deposition of HCl in the column cloud is not quite uniform with time and location because the velocity of the vehicle increases with time. Figure 2.7 shows the velocity as a function of time.

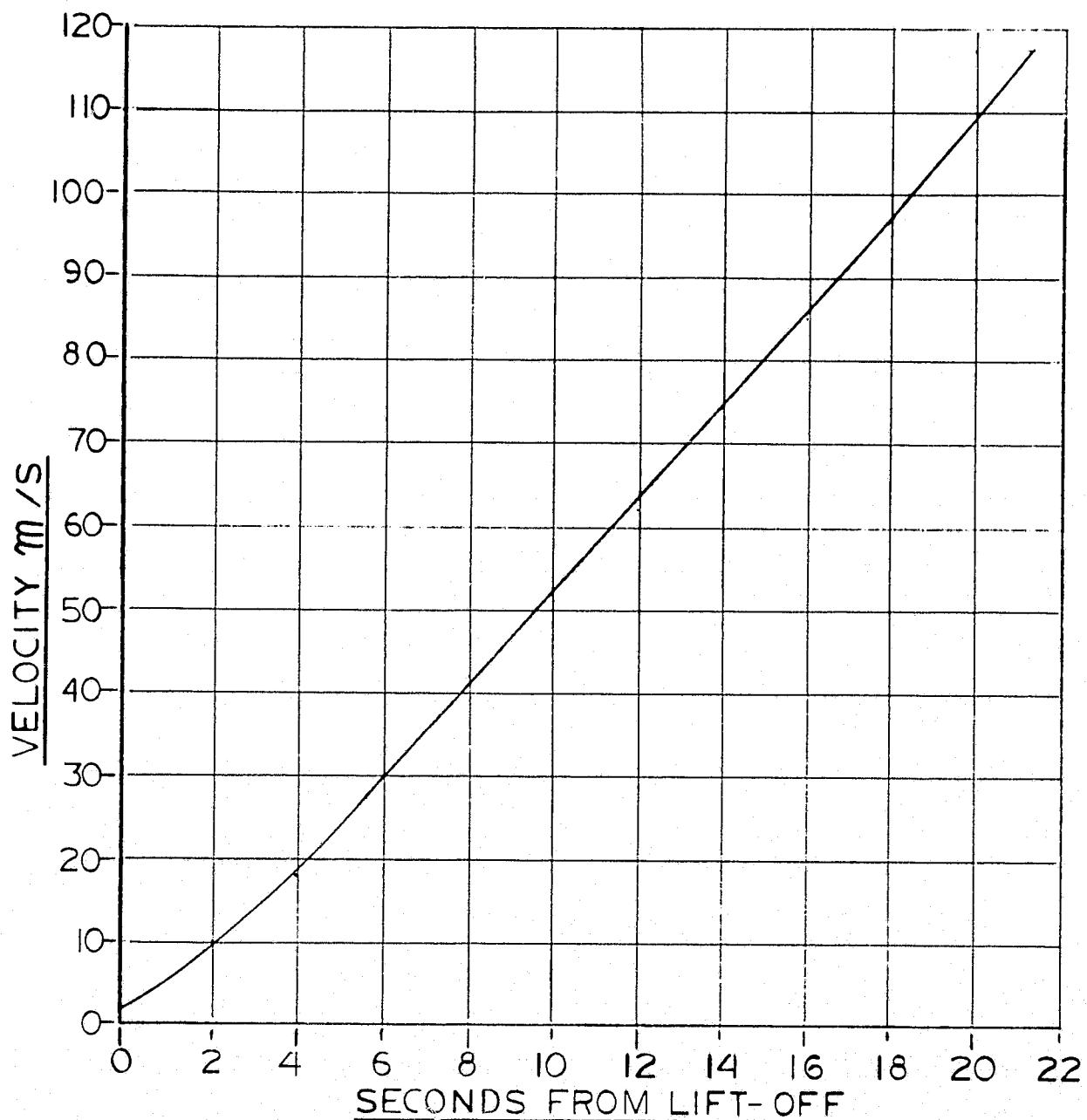
The amount of HCl deposited in the column cloud is proportional to L/V where V is the velocity of the launch vehicle. This implies that there is a change in deposition of approximately a factor of 2 between the bottom and top of the column

1 GROUND LEVEL CLOUD
2 1200 M COLUMN CLOUD
3 2000 M COLUMN CLOUD



Position of Exhaust Cloud As a Function of Time

FIGURE 2.6



VELOCITY OF VEHICLE AS A FUNCTION OF TIME

FIG.-27

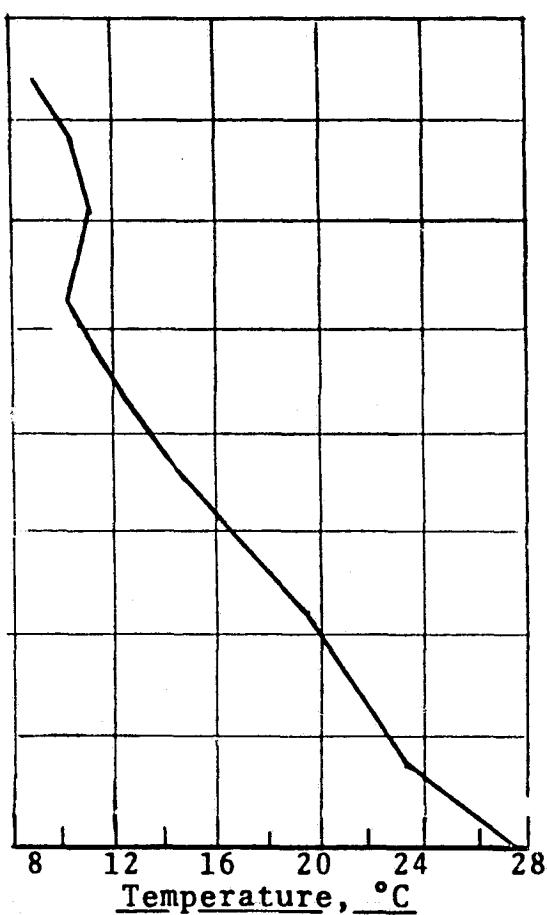
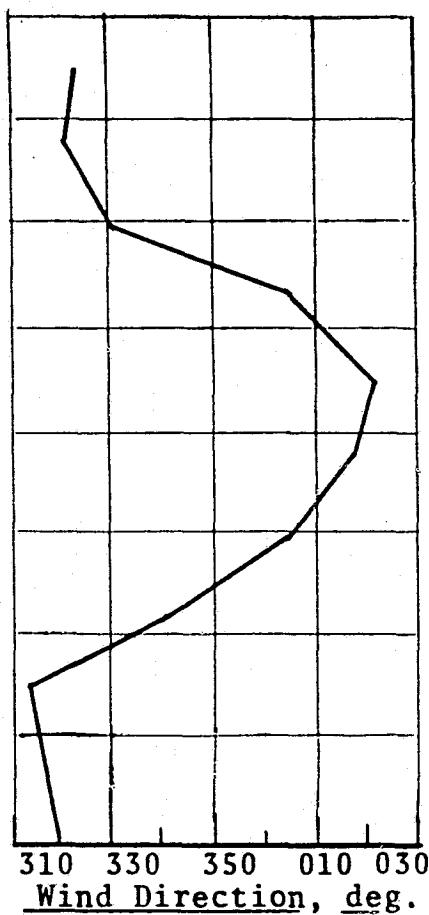
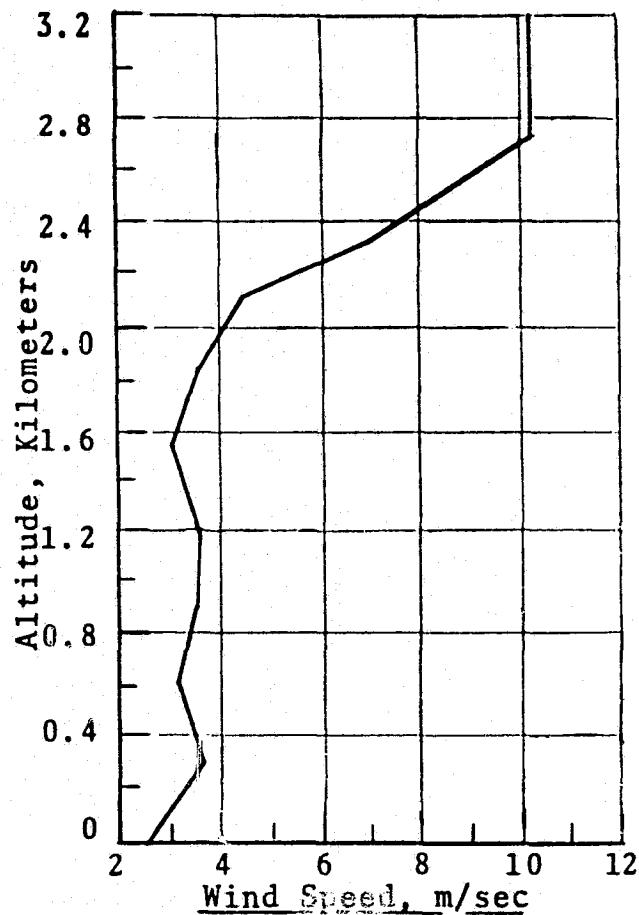
cloud at the time of formation of the cloud. Assuming that the rate of mixing of air with the cloud is basically governed by the surface area of the cloud and time, final concentration of HC1 in the stabilized cloud will be fairly constant with the bulk of the cloud having a concentration of that of the diluted ground cloud. The upper part of the column cloud which becomes one end or side of the stabilized cloud will have a somewhat lower HC1 concentration. The concentration of HC1 in terms of ppm will be a function of atmospheric conditions. If wind velocity and direction does not vary at elevations up to the inversion layer concentrations will be higher than when wind velocity and direction varies. Variations pull different parts of the column cloud in different directions and tend to increase the interface between cloud and air and increase diffusion and mixing. As a result the final cloud will be larger and show a lower concentration of HC1.

The quantity of HC1 in the stabilized cloud is a function of the altitude at which the inversion layer occurs. We will assume that the plume downstream of the vehicle is 260 m long and that the kinetic energy of this gas is essentially exhausted at this point. The velocity of the vehicle at an elevation of 2 km is 150 m/sec. The vehicle then contributes exhaust to the final cloud at the inversion layer up to the point where it reaches an altitude of approximately 2.21 km. This elevation is reached at approximately 28 sec into the flight. If the inversion layer occurs at 1.6 km, the vehicle passes through this layer at 24 sec into the flight at a velocity of approximately 135 m/sec. In this case the vehicle stops contributing to the final cloud at approximately 26 sec into the flight. Therefore, the total contribution to the final cloud will be of the order of $27 \times 1907 = 51,480 \text{ kg } \pm 5\%$.

2.3 MIXING OF GROUND CLOUD AND COLUMN CLOUD

It appears highly unlikely that the ground cloud and column cloud will mix completely. In the extreme condition the upper part of the column cloud and the ground cloud are separated by a distance of some 1-2 km. After preliminary stabilization, defined by the consumption of the kinetic energy of the exhaust gas from the rocket engine, only atmospheric conditions and diffusion processes will determine the future shape of the cloud. The data of the launch of May 20, 1975 are interesting in this respect.

Figure 2.8 shows wind speed and direction and temperature as a function of altitude. Figure 2.9 shows that on May 20, 1975 the cloud rose to an altitude of 2 km and traveled hori-



Rawindsonde Measurements at KSC, T - 0, 20 May 1975 - Titan III - AF777 Launch

Wind (Speed and Direction) As a Function of Time

FIGURE 2.8

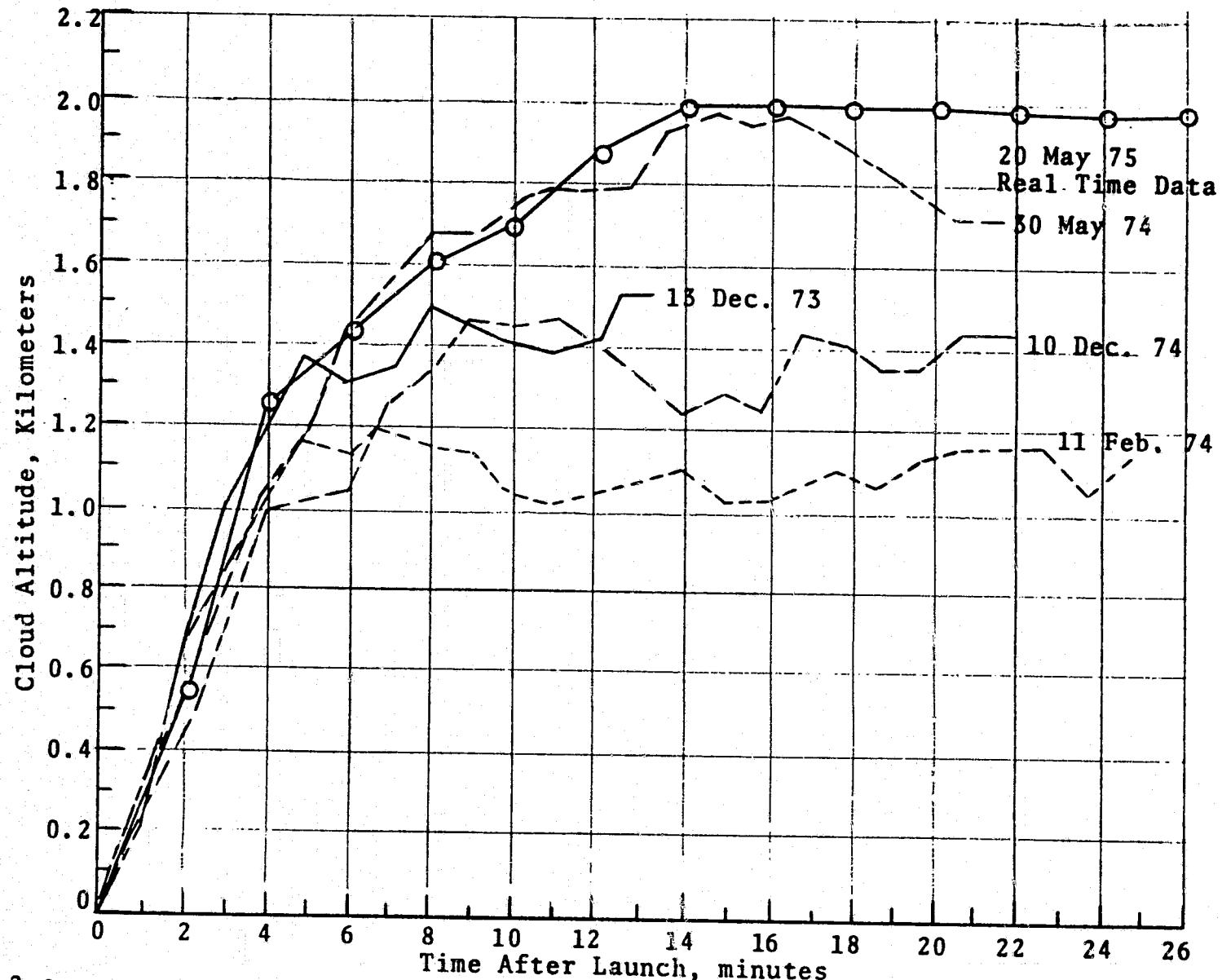


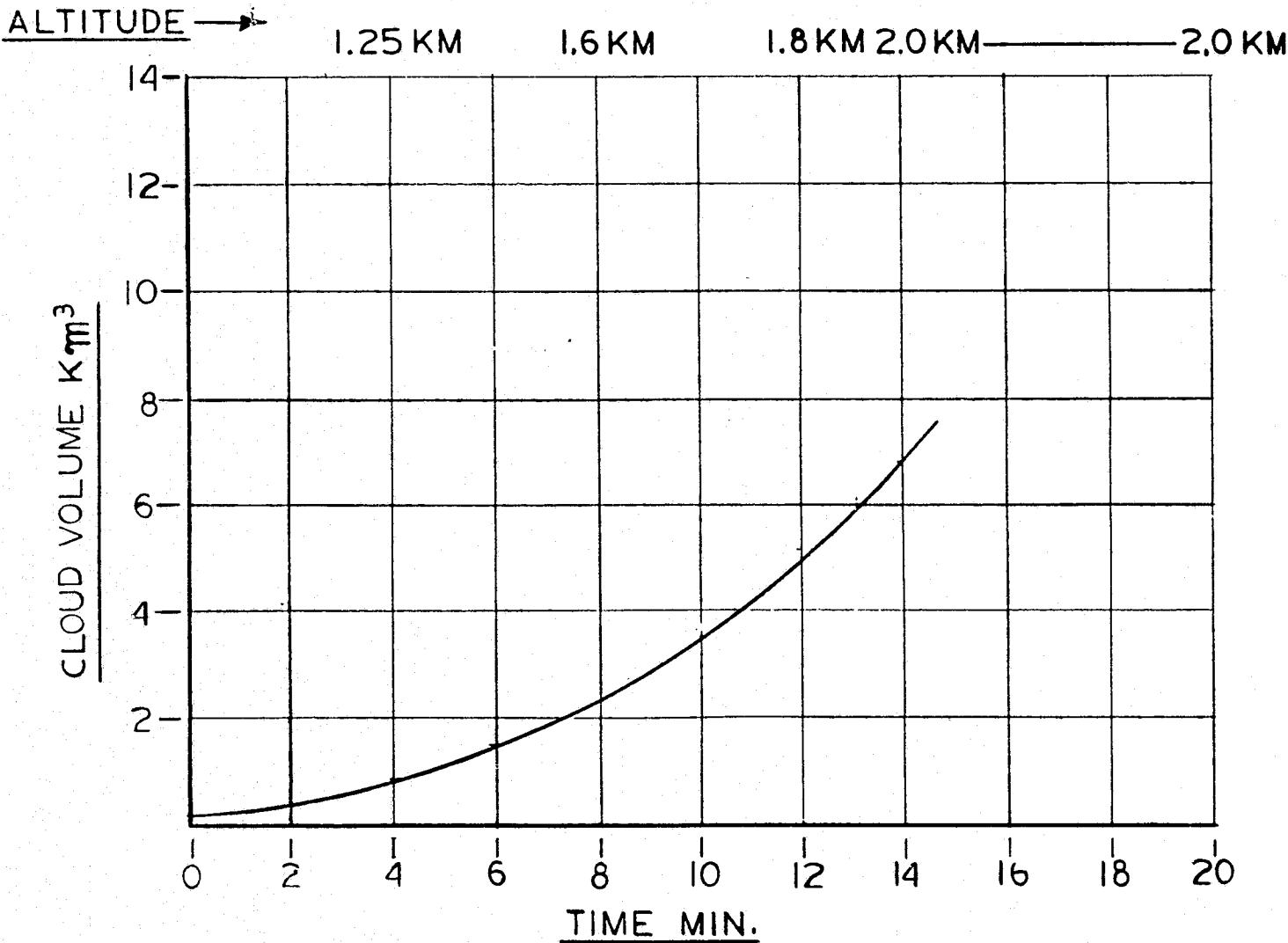
FIGURE 2.9 - Measured Titan III Cloud Rise to Stabilization - KSC Launches

zontally at that level for a period of at least 720 sec (14-26 min). Figure 2.10 is a plot of cloud growth as a function of time on May 20, 1975. This plot indicates that fast growth of the cloud occurs from 6 min on. Figure 2.9 shows that the cloud at 6 min reaches an altitude of 1.5 km and Figure 2.8 indicates that at 1.5 km altitude wind velocity increases consistently from 3.1 m/sec at 1.5 km to 4.0 m/sec at 2.0 km. This increase in wind velocity is at least partially responsible for the fast growth of the cloud of Figure 2.10. At 6 min the cloud volume is estimated at 1.5 km^3 . If a sphere, the diameter of the cloud would be approximately 600 m. The top part of the cloud travels faster than the bottom part and the change in wind velocity and direction keeps shearing the top part of the cloud. Seen from below, the linear dimension will increase from 600 m to 780 m in 5 min. An increase in linear dimension of 30% translates into an increase in volume of 2.2. The original volume of 1.5 km^3 becomes 3.3 km^3 . The value indicated in Figure 2.10 is a volume of 4.3 km^3 at 11 min.

It should be noted that directly above the inversion layer the increase in wind velocity is much more rapid. At the same time wind direction changes in the vicinity of the inversion layer and this makes the growth of the cloud two-dimensional in this area. When taking both changes in wind velocity and direction into account and assuming a finite depth of the cloud, growth of the cloud after reaching the inversion layer must be rapid.

It is quite important to know or to determine that mixing of ground cloud and column cloud will or will not occur after stabilization at the inversion layer. Concentration of HCl in the final cloud appears to be determined by the events taking place during the first 20-25 sec. However, dilution does take place as a function of time.

The delivery of neutralizing agent to the ground cloud is a relatively simple matter as described in Section 3. Rate of delivery may be varied and, if ground cloud and column cloud mix at the inversion layer, all of the neutralizing agent could be delivered to the ground cloud and be carried up to the final cloud with the ground cloud. If ground cloud and column cloud do not mix or mix insufficiently, neutralizing agent injected into the ground cloud will not be delivered to that part of the final cloud containing the column cloud. In order to reach the HCl contained in the column cloud a different technique for delivery of the neutralizing agent is then required.



CLOUD GROWTH AS A FUNCTION OF TIME

FIG-2.10

2.4 VARIATION OF TEMPERATURE OF GROUND CLOUD

All previous considerations have been based on the assumption that the ground cloud is relatively undisturbed with regard to its temperature. The rate of rise of the ground cloud is then approximately the same as that of the column cloud. If massive amounts of water will be sprayed into the ground cloud either through a system designed to lower the noise level at the vehicle or a system providing a neutralizing agent in the form of a very weak solution, temperature of the ground cloud will be reduced and its buoyancy will be affected. In that case the ground cloud will rise at a different velocity than the column cloud and it is less likely that the two clouds will mix after reaching the inversion layer.

3. DISTRIBUTION OF NEUTRALIZING AGENT IN THE CLOUD

3.1 MIXING OF NEUTRALIZING AGENT AND HCl IN THE CLOUD

Photographic evidence and the discussion of Section 2 leads to the conclusion that basically two separate clouds are formed with loose coupling between these two clouds. Airborne in-cloud gas measurements have been made during the May 20, 1975 Titan and August 20th Viking (Titan) launches. Figure 3.1 shows HCl measurements in the ground cloud at various times after launch. Two items stand out, as follows:

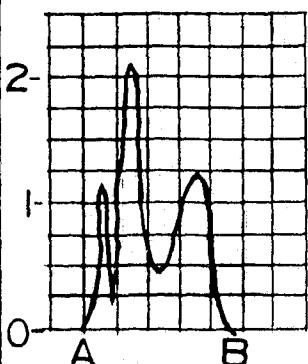
- a) The HCl concentration is already quite low at $T + 8$ min and appears to decrease with time.
- b) The HCl concentration is not constant throughout the cloud and is not the same from launch to launch. For instance, the measurement at $T + 30$ min on May 20th and $T + 33\frac{1}{2}$ min on August 20th shows a large difference. It is, of course, possible that the airplane in both cases did not fly through the same part of the cloud at that time.

The data presented in Figure 3.1 indicate that the bulk of the HCl is mixed with concentration peaks and valleys. In general, peaks show a concentration twice as large as that of the valley. The change in concentration pattern with time indicates mixing with air at the boundaries of the cloud resulting in concentration gradients from center to edge of the cloud. Figure 3.1 also shows that injection of neutralizing agent at $T + 15$ min or later requires widespread distribution on a ppm scale. Clearly, this is a difficult task since time is required to fly through the cloud and cover a large part of its volume.

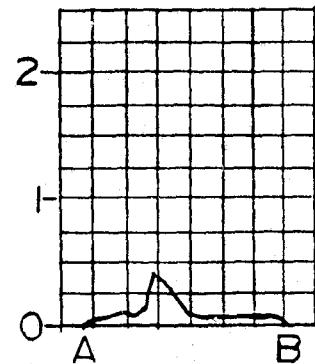
Figure 3.1 leads to the conclusion that injection of neutralizing agent in the cloud needs to be carried out at the earliest possible moment after launch. It appears that mixing of the neutralizing agent into the cloud is not much of a problem for the ground cloud. The kinetic energy of the exhaust gas will be used to mix thoroughly and it is not necessary to carefully distribute the agent during its injection. Distribution at a rate which yields uniform parts per million distribution into the column cloud appears to be a difficult problem to solve.

POINTS A & B ARE OUTER BOUNDARIES OF CLOUD

HCL. CONCENTRATION P.P.M.

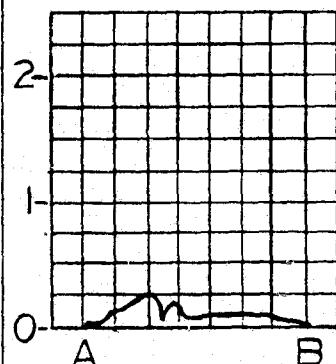


PASS 3 T+8 MIN.

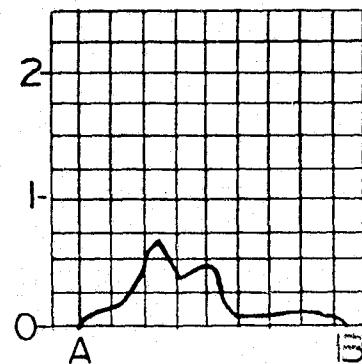


PASS 10 T+30 MIN.

HCL. CONCENTRATION P.P.M.



PASS 15 T+43 MIN.



PASS 16 T+54 MIN.

CLOUD GAS MEASUREMENTS
20 MAY 75 TITAN

FIG-3.1

3.2 INJECTION OF NEUTRALIZING AGENT INTO THE GROUND CLOUD

Neutralizing agents may be available in liquid or solid form. Delivery of the agent to the ground cloud will be considered for both phases.

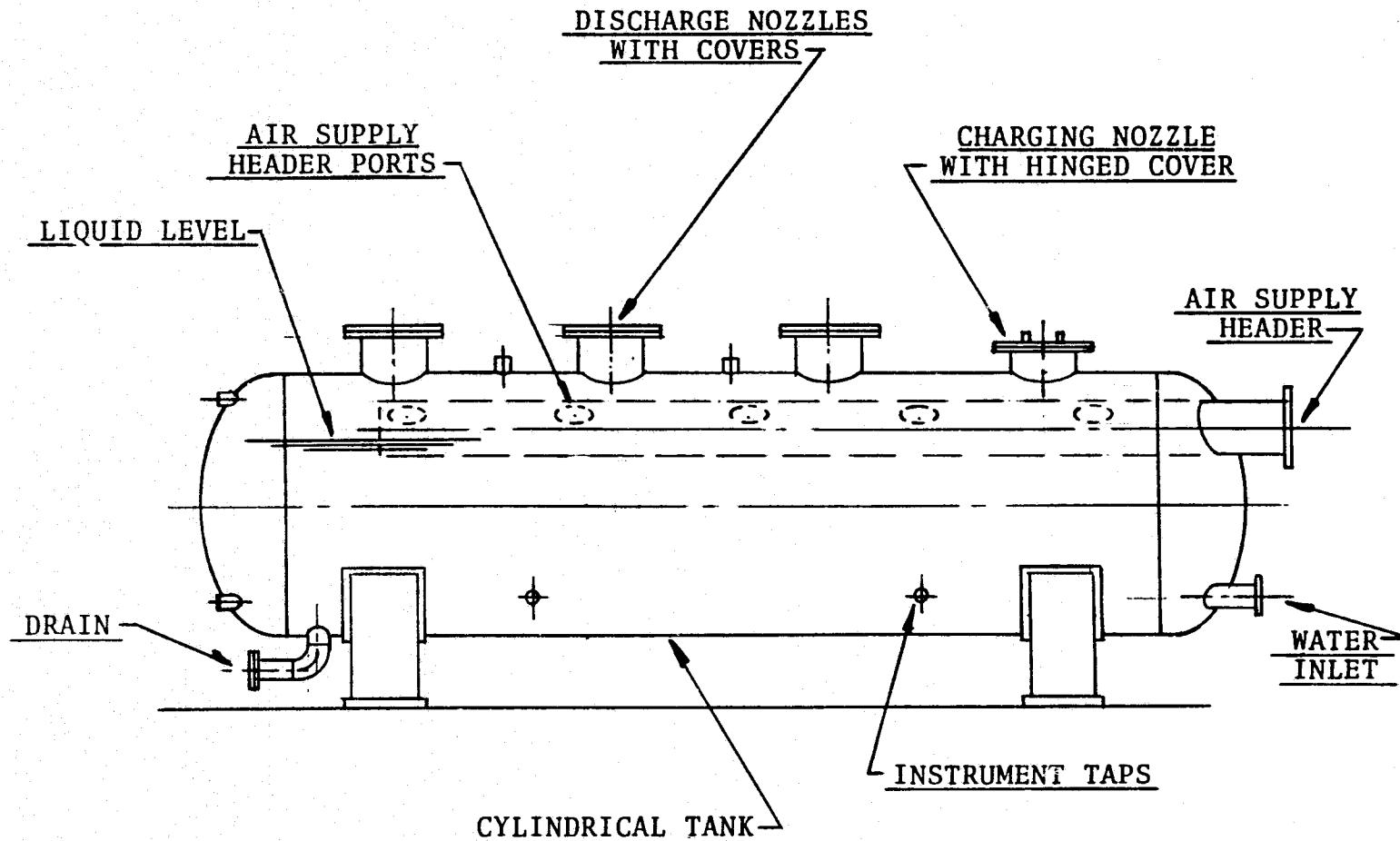
3.2.1 Delivery of Aqueous Solutions

Rate of delivery is an important variable and determines the size of the storage system. In the early part of the study it was assumed that tanks containing solutions of liquid neutralizing agent would be located at a safe distance from the downstream area of the flame trench. It turns out that some major disadvantages are associated with this kind of arrangement.

The material needs to be delivered over a time period of 6-10 sec. This requires large flow rates. This, in turn, requires large pipe diameters and results in large inventories in the pipes between storage tanks and delivery point. At the moment when flow into the cloud starts, pipes need to be full and flow rate needs to be up near the required rate. In order to achieve this flow rate all of the mass of the liquid in the pipes needs to be accelerated. This, in turn, requires a high pressure in the supply tank. Once the high flow rate is established it is very difficult to stop the flow in case of a launch abort. Valve closure needs to be timed over some seconds in order to eliminate the problem of water hammer.

After studying the formation of the ground cloud it became obvious that a much cheaper and better solution for storage and delivery of liquid neutralizing agent is available. Figure 2.1 shows that a large area downstream of the flame trench is covered by the exhaust gas during the formation of the ground cloud. Velocities are high and a great amount of turbulence leads to excellent mixing. A location with low exhaust gas temperature may be chosen.

It is proposed that the storage tank containing the solution of neutralizing agent is located directly in the path of the exhaust cloud. Figure 3.2 shows the concept of the storage tank. The neutralizing agent may be stored at atmospheric pressure and ambient temperature for indefinite periods of time prior to use. If a concentrated solution at an elevated temperature will be used, two choices are available, as follows:



Typical Neutralizing Agent Storage Tank

FIGURE 3.2

- a) Maintain the tank and contents at 40°C (103.4°F) through the use of an immersion heater with thermostat during the period of storage. No precipitation will occur at any time.
- b) Maintain the tank and contents at ambient temperature.

In the latter case the solution will be saturated and excess neutralizing agent will precipitate and be stored as a solid on the bottom of the tank. Prior to delivery heat may be added to the fluid of the tank through an immersion heater and solid will go into the solution. To speed up the process, agitation will be required. It may be feasible to eliminate the heat and agitation process and to deliver liquid and solid into the cloud simultaneously. Solid will be fluidized and carried by the liquid through the nozzles of the storage vessel. Delivery of liquid is by pressurization of the vapor space above the liquid from an external high pressure gas source. The pressure to be maintained above the liquid is relatively low (15-50 psig). The pressure is primarily governed by the distance over which the liquid needs to be sprayed.

Advantages of the proposed system are many. They are:

- a) Elimination of long, large diameter liquid pipes.
- b) Lowering of gas requirements for pressurization.
- c) Low pressure storage of the solution prior to use.
- d) It is not necessary to accelerate a large mass of liquid during startup.
- e) Small size of both liquid and gas storage tanks.
- f) It is possible to abort delivery of the solution by relieving the gas pressure in the vapor space of the liquid tank.

3.2.2 Delivery of Solid Neutralizing Agents

Neutralizing agents in the form of solids need to be ground to very fine particles before delivery into the cloud. If particles are large, gas diffusion rather than reaction kinetics becomes the governing factor for removal of the HCl from the cloud. The simplest way of delivery of the solid material is by spreading it out on the ground over which the cloud travels. The particles will be picked up and entrained by the high velocity exhaust gas traveling over the material. Obviously, there will not be much control over the rate of

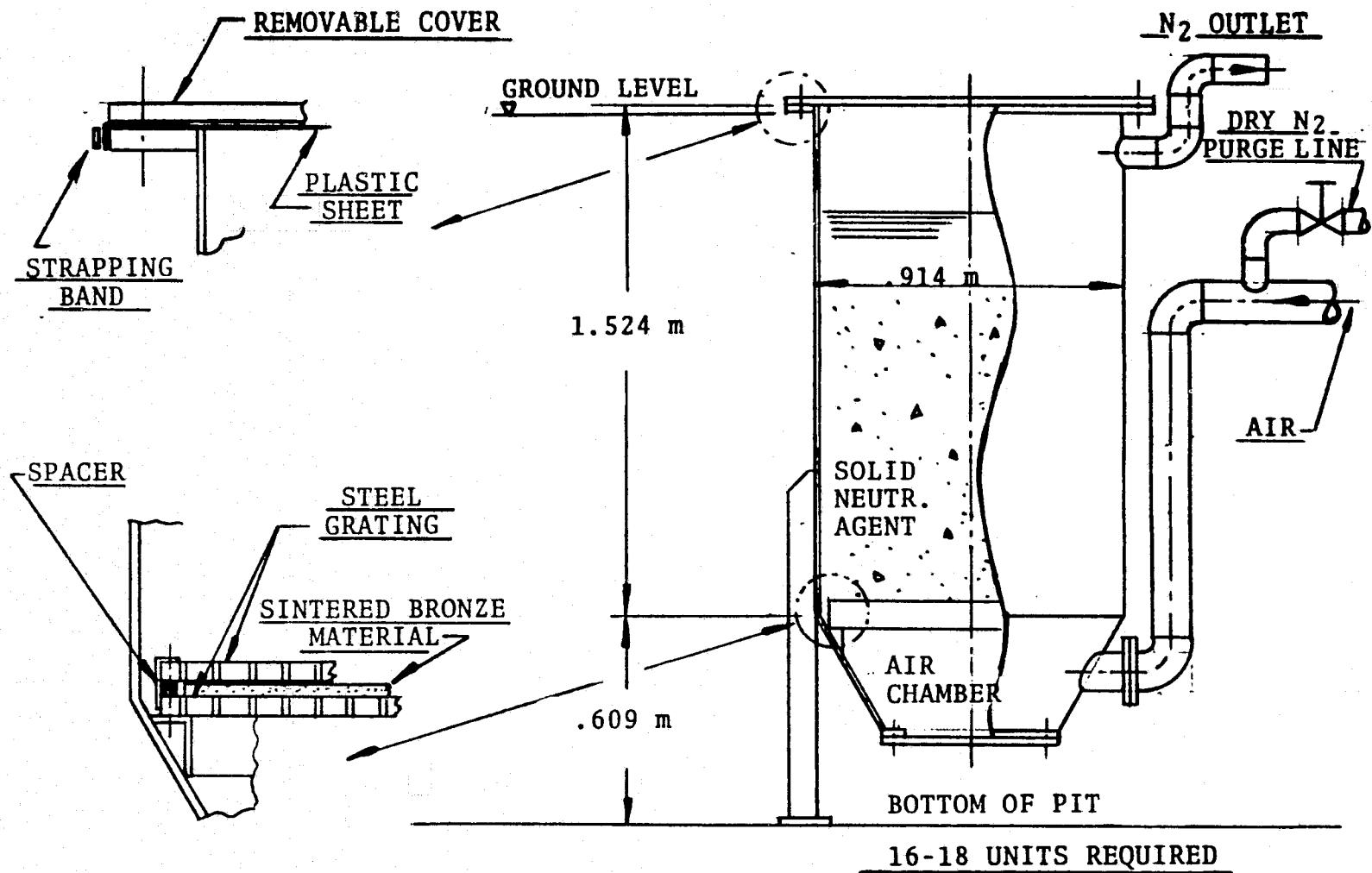
delivery. Better control is exercised by feeding the solid as a fluidized material from a container. The material may be fluidized by means of a gas stream.

Figure 3.3 shows a conceptual design of a system capable of delivering fluidized solid neutralizing agent to the cloud. The figure shows one container. In order to spread delivery of the solid throughout the cloud, a number of containers can be spread throughout the area over which the cloud travels. Each container is equipped with a lid to protect the solid granular material from moisture. Drying of the material may be accomplished by feeding a dry gas through the porous bed at a low flow rate before use. Lids need to be removed prior to a launch as part of the launch sequence. The rate of gas flow required to fluidize the bed is a function of particle size and bed height. Fluidizing will occur as soon as the product of pressure drop and cross sectional flow area equals the weight of the bed. When the gas pressure sufficiently exceeds this value, particles will be lifted out of the bed and thrown into the stream of exhaust gas.

3.3 INJECTION OF NEUTRALIZING AGENT INTO THE COLUMN CLOUD

The column cloud to be seeded with the neutralizing agent is between 1,000-2,000 m tall and has a diameter of the order of a few hundred m. The column may be reached by aircraft approximately 2-4 min after launch. Assume that the aircraft flies at a speed of 120 mph through the cloud and that it can complete a Figure 8 in 40 sec. It then traverses the cloud three times per min. If the cloud diameter is 200 m, spraying of the agent takes place during 17% of the time. If the airplane can deposit agent over a cross section of 200 m, the volume covered after one Figure 8 is $68,000 \text{ m}^3$. The volume of the cloud is of the order of $4.8 \times 10^7 \text{ m}^3$ ($2,000 \text{ m}$ high). To cover it fully requires 708 Figure 8's or approximately 8 hr of flying. It should be realized that the cloud during this time grows considerably in volume. Clearly, a different technique needs to be used to release a large quantity of neutralizing agent in a short time and allow it to fall through the cloud. During the fall it is expected to break up and disperse.

Fire fighting of forest fires employs the technique of air drops of large quantities of fire retardant chemicals. The objective in these drops is to have as large a fraction of the initial drop as possible reach the ground and to cover the ground area uniformly.



Delivery System for Solid Neutralizing Agents

FIGURE 3.3

The requirements at KSC are different, as follows:

- a) Practically none of the neutralizing agent or solution should reach the ground.
- b) Good dispersion and a high rate of vaporization are required.
- c) Horizontal velocity of the injected agent in the direction of flight should preferably be zero or very small.

4. MECHANISM BY WHICH HYDROGEN CHLORIDE WOULD BE REMOVED FROM THE CLOUD BY NATURAL PHENOMENA

4.1 INDUSTRIAL EXPERIENCE

Hydrogen chloride emissions to the atmosphere occur from a number of industrial operations. Early effects of hydrogen chloride on vegetation were noted in Great Britain in a 1951 report (ref. 3). Detailed a classic case in 19th century England, "In the early days of the leblanc soda process, most of the hydrogen chloride from the treatment of salt with sulfuric acid was wasted to the atmosphere, causing extensive damage to plants near the factory."

Present-day hydrogen chloride emissions occur from hydrochloric acid manufacturing, incineration of industrial and commercial waste, and the combustion of coal. In a 1966 Department of Health Service report (ref. 4) a summary of the emission of HCl from hydrochloric acid plants found stack emissions in a range of traces of HCl to 4 kg of HCl per MT of acid manufactured. The average HCl emission to the atmosphere for the acid processes is .23 kg of HCl per MT of acid produced. For the 1966 acid production of 1.6×10^6 MT this results in 400 MT of hydrogen chloride emissions per year. Ledbetter reported (ref. 5) that the combustion of coal in power generation and residential heating releases .034 to .129 kg HCl contamination per 10^9 J released.

A rough indication of total HCl release into the atmosphere may be made on the basis of this number. Assume a residence to use in winter 30×10^6 J/day and assume a metropolitan area of 500,000 people with some 50,000 residences emitting HCl at the postulated rate. Total emission is then of the order of 50-200 kg/day. A report on refuse incinerators in Japan (ref. 6) indicated that HCl emissions were high where rubbish was burned, sometimes reaching 2,000 ppm. The 1973 University of Michigan NASA Report (ref. 7) indicates that the estimated total annual industrial U.S. hydrogen chloride emission is 5×10^6 MT. The report also presents the results of an extensive survey of literature. An extensive library of over 200 volumes on air pollution exists at the Argonne National Laboratory library. A review of the above literature shows that hydrogen chloride contamination of the environment has not been regarded as a serious health problem. For this reason, available data on toxic effects are limited.

Table V is a summary of various standards for human exposure to HCl from the University of Michigan report. The table indicates a wide discrepancy between allowable limits for various countries. Tables VI through VIII, on the effects of HCl on humans, animals and plants have been reproduced from the work of Stahl (ref. 8).

In addition to the summary of literature review prepared by Stahl, an annotated bibliography of hydrochloric acid and air pollution was prepared by the Environment Protection Agency, 1971 (ref. 9). This publication lists twenty-nine references of emission sources, twenty-nine references of measurement methods, fifteen references of effects on human health and six references of effects on plants and livestock.

4.2 LITERATURE REVIEW

Following is the annotated bibliography from the University of Michigan Report, NASA No. CR-129003 (ref. 7):

Annotated Bibliography

Stahl, Quade R. Preliminary Air Pollution Survey of Hydrochloric Acid. A Literature Review. U. S. Department of Health, Education and Welfare. National Air Pollution Control Administration, 1969.

Probably most complete survey up to that time. Tables VI, VII and VIII summarize results of various studies in easily usable form. The report is not "a synthesis of available information but rather a summary without an attempt to interpret or reconcile conflicting data." There are major conflicts though as can be seen from scanning the tables. Some of them arise because the data are from experiments performed many years ago when accurate measurements and control of HCl concentrations may have been difficult. The present author is unable to evaluate the problems in the studies in man and other animals. In most cases of the studies on plants, the data in Table VIII are from abstracts or reports of field observations where the information for evaluating the accuracy are either not given or were unavailable to the author.

Two things stand out from Table VIII: (1) Different plants have different susceptibilities to HCl. (2) Almost all experiments are short term. There are virtually no studies covering several generations (to consider effects on reproduction) or cumulative effects of low level repeated or continuous exposure.

T A B L E V
Human Exposure Standards for HCl

<u>Maximum Allowed Con- centration (ppm)</u>	<u>Time Period</u>	<u>Conditions</u>	<u>Country</u>	<u>Stahl Ref.</u>
0.009	24 hr average	ambient air quality	USSR	86
0.02	24 hr average	ambient air quality	Czechoslovakia	84
0.03	single exposure		USSR	86
0.07	single exposure		Czechoslovakia	84
0.5	30 min average	ambient air quality	West Germany	55
1.0	30 min average	max. allowable	West Germany	55
5.0		work station	West Germany	55
5.0	8 hr day / 5 day week		U.S.	111

(above data from Stahl)

				<u>Ref.</u>
2	1 hr average	general public	U.S.	NAS/NRC 1971
2	30 min average	general public	U.S.	NAS/NRC 1971
4	10 min average	general public	U.S.	NAS/NRC 1971
3	1 hr average	general public- emergency limits	U.S.	NAS/NRC 1971
3	30 min average	general public- emergency limits	U.S.	NAS/NRC 1971
7	10 min average	general public- emergency limits	U.S.	NAS/NRC 1971
10	1 hr average	controlled (work sta)pop. short- term emergency limits	U.S.	NASA 1968

TABLE V (Continued)

Maximum Allowed Con- centration (ppm)	Time Period	Conditions	Country	Ref.
20	30 min	controlled (work sta)pop. short- term emergency limits	U.S.	NASA 1968
Ref. NAS/NRC-1971 = "Guide for Short-term Exposure of the Public to Air Pollutants, II. Guide for Hydrogen Chloride. (Nat. Advisory Center on Toxicology NAS, NRC, Aug. 1971)				
NASA/1968	= "Compendium of Human Responses to the Aerospace Environment", Vol. III, NASA CR1205 (111), Nov., 1968.			

T A B L E V I
Summary of Reported Effects of Inhalation of
Hydrogen Chloride by Humans

Concentration (ppm)*	Exposure Time	Effects or Comments
50-100		Work is impossible
10-50		Work is difficult but possible
10		Work is undisturbed
1300-2000	Few min	Lethal
1000-1300	30-60 min	Dangerous
50-100	60 min	Intolerable
35		Irritation of throat after short exposure
1000-2000		Brief exposures are dangerous
10		Irritation
5		No organic damage
10		Odor threshold value
0.067-0.134		Odor threshold value

TABLE VI (Continued)

<u>Concentration (ppm)*</u>	<u>Exposure Time</u>	<u>Effects or Comments</u>
0.402		Concentration for threshold reflux effect on optical chronaxic
0.134		Concentration for threshold reflex effect on eye sensitivity to light
0.335		Concentration for threshold effect on digito-vascular toxicity
0.067-0.134		Threshold concentrations of change in the rhythm and depth of respiratory movement
1-5		Odor threshold value

*1 ppm = $1,470 \mu\text{g}/\text{m}^3$ @ 25°C .

T A B L E V I I

Summary of Reported Effects of Inhalation
of Hydrogen Chloride on Animals

<u>Species</u>	<u>Concentra- tion (ppm)*</u>	<u>Exposure Time</u>	<u>Effects or Comments</u>
Rabbits	4300	30 min	Fatal in some cases, due to laryngeal spasm, laryngeal edema, or rapidly developing pulmonary edema
Guinea pigs	4300	30 min	Fatal in some cases, due to laryngeal spasm, laryngeal edema, or rapidly developing pulmonary edema
Cats	3400	90 min	Death after 2-6 days
Rabbits	3400	90 min	Death after 2-6 days
Guinea pigs	3400	90 min	Death after 2-6 days
Cats	1350	90 min	Severe irritation, dyspnea and clouding of the cornea

TABLE VII (Continued)

<u>Species</u>	<u>Concen-tration (ppm)*</u>	<u>Exposure Time</u>	<u>Effects or Comments</u>
Rabbits	1350	90 min	Severe irritation, dyspnea and clouding of the cornea
Guinea pigs	1350	90 min	Severe irritation, dyspnea and clouding of the cornea
Rabbits	670	2 hr	Fatal in some cases
Guinea pigs	670	2 hr	Fatal in some cases
Rabbits	300	6 hr	Corrosion of the cornea and upper respiratory irritation
Guinea pigs	300	6 hr	Corrosion of the cornea and upper respiratory irritation
Rabbits	100-140	6 hr	Only slight corrosion of the cornea and upper respiratory irritation
Guinea pigs	100-140	6 hr	Only slight corrosion of the cornea and upper respiratory irritation
Rabbits	100	6 hr/day for 50 days	Slight unrest and irritation of the eyes and nose
Guinea pigs	100	6 hr/day for 50 days	Slight unrest and irritation of the eyes and nose
Pigeons	100	6 hr/day for 50 days	Slight unrest and irritation of the eyes and nose
Monkey	33	6 hr/day 5 days/wk for 4 wks	No immediate toxic effects and no pathological changes
Rabbit	33	6 hr/day 5 days/wk for 4 wks	No immediate toxic effects and no pathological changes
Guinea pig	33	6 hr/day 5 days/wk for 4 wks	No immediate toxic effects and no pathological changes
Rabbits	60	5 min	Cessation of ciliary activity without recovery
Rabbits	30	10 min	Cessation of ciliary activity without recovery

*1 ppm = 1,470 $\mu\text{g}/\text{m}^3$ @ 25°C.

TABLE VIII

Summary of Reported Toxic Effects of
Hydrogen Chloride Exposure on Plants

<u>Species</u>	<u>Concentra- tion (ppm)*</u>	<u>Exposure Time</u>	<u>Effects or Comments</u>
Plants	10-50		No leaf damage
Plants	100-1000		Leaf damage
Sugar beets	10	Few hr	Threshold for marking
Viburnum seedlings	5-20	24 hr	Leaves rolled at the edges, withered, shrunk, faded and necrotic
Beech	1000	1 hr	Local lesions produced
Oak	1000	1 hr	Local lesions produced
Maple	2000		Marginal leaf scorch
Birch	2000		Marginal leaf scorch
Pear	2000		Marginal leaf scorch
Viburnum seedlings	5-20	48 hr	Plants died
Larch	5-20	48 hr	Plants died
Fir	1000	1 hr	Local lesions formed
Spruce	2000	1 hr/day for 80 days	No apparent injury
Tomato plants	5	2 hr	Developed interveinal bronzing followed by necrosis within 72 hrs after exposure
<u>Liriodendron tulipifera</u>	3	4 hr	Threshold for visible injury
<u>Ainus glutinosa</u>	6	4 hr	Threshold for visible injury
<u>Prunus serotina</u>	6	4 hr	Threshold for visible injury
<u>Acer saccharus</u>	7	4 hr	Threshold for visible injury
<u>Acer plata- nooides</u>	7	4 hr	Threshold for visible injury
<u>Quercus rubus</u>	13	4 hr	No visible injury
<u>Pinus strobus</u>	8	4 hr	Threshold for visible injury

TABLE VIII (Continued)

<u>Species</u>	<u>Concentra- tion (ppm)*</u>	<u>Exposure Time</u>	<u>Effects or Comments</u>
<u><i>Pseudotsuga mantissii</i></u>	10	4 hr	Threshold for visible injury
<u><i>Abies balsamea</i></u>	10	4 hr	Threshold for visible damage
<u><i>Pinus abies</i></u>	19	4 hr	Threshold for visible damage
<u><i>Pinus nigra</i></u>	18	4 hr	No visible damage
<u><i>Thuja occi- dentalis</i></u>	43	4 hr	No visible damage
<u>Spruce seedlings</u>	< 50	20 min	Plants die

*1 ppm = 1,470 $\mu\text{g}/\text{m}^3$ @ 25°C.

Bibliographic Sources

- *Air Pollution Abstracts (Monthly) - U. S. Environmental Protection Agency Air Pollution Technical Information Center (APTIC) Research Triangle Park, N.C. 27711
- Air Pollution Abstracts (Monthly) - Department of Trade and Industry (Britain) Warren Spring Lab.
- *Toxicity Bibliography (Monthly) - U. S. Public Health Service - Library of Medicine
- Toxicity Information Program - National Library of Medicine will do literature search on request. (See example attached)
- Air Pollution Technical Information Center - Research Triangle Park, N. C. 27711, will do literature search on request (not used)
- Hydrochloric Acid and Air Pollution: An Annotated Bibliography - U. S. Environmental Protection Agency, Research Triangle Park, N. C. (1971) pp. 51-64 deal with effect on humans

Bibliographic Sources (Continued)

Hydrochloric Acid and Air Pollution: An Annotated Bibliography (Continued) - (9p) and on plant and live-stock (4p) (a one-shot thing, apparently)

*Best sources for continuing review of (relatively) current literature.

NOTES: General abstracting journals such as Chem. Abstracts or Biographical Abstracts can be used but are generally inefficient. The toxicity information program search did give Chem. Abstract or Biol. Abstract references so that if nothing else, we have the abstracts. Another source, once one has several articles located is the Science Citation Index (which tells which other authors have referred to the paper of interest). This has not proved particularly rewarding either. Key word indexes in Chemical Titles and Biographical Abstracts are also useful for keeping up with current material.

Semi-annotated Listing of Other Articles of Interest

Arndt, V. "Konzentrations Aenderungen bei Bleefforsotoffen unter dem Einfluss von Luftverunreinigungen. Ein Diskussionalbeitrax Zun Pignent Analyse," Environmental Pollution 2, 37-48 (1971).

Reports that B-carotene is a better indicator of damage than chlorophylls are. Finds that 0.5 mg/m³ HCl (ca. 0.34 ppm) (exposure time not clear - could be several (6-10) months results in 20% to 35% lower chlorophyll upon treatment with acid - in vitro. (If the reading of German is right, this could be one report of long-term, low-level exposure - and there is an effect, at least on pigment concentration.)

Baetjer, A. M. "Chronic Exposures to Air Pollutants and Acute Infectious Respiratory Diseases", Arch. Ind. Hyg. and Occupational Medicine 2, 400-406 (1950) (Source: Air Pollution Abst. (U.S.) Vol. 2 (6), 10857)

Quote from abstract: "Data available at present are insufficient to draw conclusion".

Berge, H. Phytotoxisch Immissionen (P. Parcy, Berlin, 1963)
pp 51-53 (on HC1)

Description of properties of HC1, macroscopic and microscopic descriptions of damage, basis of effects, diagnosis of plant. References (few are given) are primarily in the 1930's.

Berry, C. R. "A Plant Fumigation Chamber Suitable for Forestry Studies," Phytopathology 60, 1613-1615 (1970)

(Article not read. Included in case someone wants to get into experimental work or wants to track somebody down who might do experimental work.)

Boray, E. "The Effects of Air Pollution on Plants," (in French) in Probleme der luft verumreinigung durch die Industry (ed. (not recorded in my notes) (Vogt-Schild S. A., Switzerland, 1969)
pp 1-19, 126 references.

(Mostly on SO₂, may have some references on HC1 - which is why it's mentioned here. Sources: Air Pollution Abstracts (U.S.) Vol. 2 (#6), 10994.1.

Cesta, R. P. and M. E. McLouth "Launch Conditions Produced by the Titan III-C Launch Vehicle", Amer. Inst. Indust. Hyg. J. 30 635 - 639 (1969).

Included here because it contains actual measurements of HC1 concentrations. Techniques and values - and their reliability - are worth looking at.

Daessler, H. G. and Ewart "Damage to plants Caused by Hydrogen Chloride", Biologische Zentralblatt 88 209 - 213 (1969).

(Chem. Abstracts 71 7367f: exposure of plants to 0.05 - 2.0 mg/m³ HC1 (0.03-1.3 ppm) resulted in a Cl ion content of up to 20 times that in the controls. (damage and HC1) concentration were proportional at lower concentrations).

Anon. European Congress on the influence of Air Pollution on Plants and Animals, First Proceedings. Air Pollution (Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands, 1969).

Included here primarily as information on its existence. It does not appear to have much, if any, discussion of HC1.

Ewart, E. "Die Einwirkung von Chlorwasserstoff auf Pflanzen in Experiment", Polsha Ahal Nauk... (See Air Pollution Abstracts, Vol. 2 (#11) 14624) - (for abstract's complete reference).

Under intermittent gassing (test periods between 50 and 470 hrs) there was no damage when "maximum permissible emission concentration of 0.05 mg/m^3 ($\sim 0.03 \text{ ppm}$) was not exceeded. At 2.0 mg/m^3 ($\sim 1.4 \text{ ppm}$), peas or beans showed "first symptoms of necrosis after eight hrs" (if plants were removed at this stage some leaves died and fell off, but plant survived and produced new, undamaged leaves). After 100 hrs at the higher concentration all plants died. (This may be the same Ewart working with Daessler, above. If we continue to keep eye on literature, his name may be one to look out for.)

Godish, T. J. Effects of Hydrogen Chloride Gas on Photosynthesis, Respiration, Transpiration, and Photosynthetic Pigments of Tomato C. V. Bonny Best Ph.D. Thesis Pennsylvania State University, 1970.

Found effects on transpiration (water loss, important in cooling the plant), respiration and photosynthesis at both high and low exposure (8-10 ppm for 2 hrs = high 70 pphm for 10 hrs per day times 2 days or 40 pphm for 8 hrs per day times 7 days = low). Effects were dependent on growing season and in some cases on humidity. Depending on exposure he found increase or decrease in respiration and photosynthesis, (making explanation of response difficult). In all cases, studies were made within 24 hrs of exposure (what happens in the long term? - not answered.)

Abstract concludes: "The most significant findings of this study were: (1) changes in respiration and transpiration would be induced in the absence of visible symptoms; (2) visible symptoms in the form of chlorosis (loss of color) may have little to do with plant debilitation, especially under saturating light intensities; and (3) HCl gas, supposedly acidic does not convert chlorophyll to pheophytin at low concentration exposures." (2) means that plants can still photosynthesize, at least shortly after damage occurs, even though they show spotting, etc. There are serious problems in accepting conclusion (3) from a reading of the thesis. A great deal of experience in chlorophyll measurements and the data presented in thesis indicates that there

were major deficiencies in the experimental procedure so that the conclusion is not a reliable one. This casts a bad light on the other conclusions although they may be o.k. One point is clear: There are physiological effects on plant processes which are not always immediately evident from the external appearance of the plant. These physiological effects may be significant for the long term survival and growth of the plant under low levels of exposure.

Heck, W. W. "Symptomology of Injury to Vegetation by Other Pollutants".

Section XI: 1-20, in Lacasse and Moroz, Editors, Handbook of Effects Assessment - Vegetation Damage (CAES, (CAES: Center Air Environment Studies) The Pennsylvania State University, University Park, (1969).

Hindawi, I. J. "Injury by Sulfer Dioxide, Hydrogen Fluoride and Chlorine as Observed and Reflected on Vegetation in the Field." J. Air Pollution Control Assn. 18, 307-312 (1968).

At one half maximum plant operations, smokestack was emitting 119-473 ppm HCl and 0.5 - 0.9 ppm Cl₂. Article has pictures of damaged plants. Residents had complained of acid mist smell and variety of ornamental plants were damaged including necrotic spotting and decay of leaf margins. Early leaf abscission (falling off of leaves) was also observed.

Hindawi, I. J. Air Pollution Injury to Vegetation (N. S. Public Health Service, National Air Pollution Control Administration, 1970) 44 pp.

(not seen)

Il'kum, G. M. "Effect of Toxic Gases on Plants" (in Russian) Fiziol. Biokhim. Kul't Rost. 3, 87-92 (1971) (In Chem Abstract, Vol. 59) (Source: Air Pollution Abstracts - British).

K⁺, Na⁺, Ca²⁺ occur in greater amounts in trees living near industrial plants giving off HCl. (This is consistent with findings of Daessler and Ewart and of Shriner and LaCasse (see these papers) which indicate large increase of Cl⁻ in HCl treated plants. The cations above would be picked up at the same time to give total charge neutrality. H⁺ is probably neutralized by soil, or and the pH maintained (relatively) constant by uptake of plant roots).

Kisser, J. "Physiologische Probleme der Einwirkung von Luftverunreinigung auf die Vegetation." Polsha Ahad Nauk... (See Air Pollution Abstracts, Vol. 2, (#11) 14636 for abstract and complete reference) "exposure of plants to hydrochloric acid caused a depression of the water balance" ... (see also Godish. This could also be due to increased salt content; see Daessler and Ewart, Il'kum, and Shriner and LaCasse).

Konstantinov, A. V. "Disturbances of Meiosis in Some Plants under the Effects of Hydrochloric Acid". Genet. Tsitol. 191-199 (1970) (in Russian) See Chem. Abst. 76 54771g.

Treatment of flowers of variety of plants with 0.047 HCl solution before meiosis in the anthers (process of cell division during pollen formation) caused severe aberrations in cells and chromosomes. A pH decrease of 0.8 was observed in some cell nuclei. (This paper is known only from Chem. Abstracts. Despite the fact the work was done with HCl solutions it has profound implications regarding the effect of HCl in the reproduction of plants.)

Lind, C. T. and S. A. London "Exposure of Marigold (Tagetes) to Gaseous Hydrogen Chloride", (U. S. Nat. Tech. Inform. Service AO Report #732195 (18pp) 1971. See also Chem. Abstracts 76, 76073r and government reports announcement 71(24)31.

From Chem. Abstracts: all plants died after five min exposure to 2071 ppm HCl. At 96 ppm no effect was noted.

Means, W. E., Jr., and M. C. Lacasse "Relative Sensitivity of 12 Tree Species to HCl Gas". Phytopathology, 59, 401, (1959) Abstract.

(While only an abstract it does summarize data; e.g. *Liriodendron tulipifera* had visible injury after 4 hrs exposure to 3 ppm HCl. Others were more tolerant. Message Sensitivity is species specific, at least.)

Ryabuskina, Zh. P. "Eye Lesions in the Hydrochloric Acid Industry" Vestn. Oftamol. 3, 76-77 (1970) (in Russian?) c.f. Biol. Abst. 5258106.

Shriner, D. S. and N. L. LaCasse "Rapid Determination of Chloride Content of Vegetation for Assessment of Air Pollution Injury from Hydrogen Chloride", Phytopathology 62, 412-429 (1972).

Exposure to tomato and chrysanthemum to 2-18 ppm HCl for 1-3 hrs resulted in large amounts of Cl⁻ in leaves. "The procedure has potential usefulness as a diagnostic tool in assessment of air pollution injury from HCl gas."

Thomas, M. D. "Effects of Air Pollution on Plants" in Air Pollution (WHO Monograph Series, #46) Columbia Univ. Press, N. Y., 1961, pp 233-278.

Thomas, M. D. "Gas Damage to Plants", Ann. Rev. Plant Physiology, 2, 293 (1951).

Has two paragraphs on HCl. According to Thomas, older literature implies that threshold concentration for visible marking was 50-100 ppm. Thomas and coworkers found threshold for sugar beets is 10 ppm for several hours.

Tolo, K. J., et al. "Acidified Drinking Water and Dental Enamel in Rats", Z. Versuchsterk, 11: 229-233 (1969).

This reference was run across a couple of times but could never be tracked down. It is intriguing in the same way that the Ryabuskina reference is - except more so.

The following technical articles have also been studied in more detail as follows:

Machle, W., et al. "The Effect of the Inhalation of Hydrogen Chloride", J. Ind. Hyg. Toxicol., 24: 222, 1942.

Because of its corrosive action the gas primarily affects the respiratory tract. Damage in the form of edema, necrosis, and hemorrhaging occurs to tracheal, bronchial and alveolar epithelium as well as pulmonary blood vessels, interstitial tissues and pulmonary alveoli. Damage can also occur to liver and kidneys in severe cases where death results. In addition, hearts in dead animals occasionally showed massive myocardial infarctions.

Daessler, H. G. and Ewart, E. "Damage to Plants Caused by Hydrogen Chloride", Biologische Zentralblatt, 88, 209-213, 1969.

Damage to plants in the emissions areas of chemicals and potash may be diagnosed, not only by air analysis, but

by determination of chloride in damaged plants. In various plants experimentally exposed to HCl gas chloride levels up to 20 times critical values were found, which persisted long after exposure was ended. At lower concentrations, damage and HCl concentration were proportional."

Heck, W. W. "Symptomology of Injury to Vegetation by Other Pollutants", Sec. IX: 1-20, Handbook of Effects Assessment-Vegetation Damage CAES, Lacasse and Moroz, Editors, Pennsylvania State University.

A separate letter has been written requesting this document.

Thomas, M. D. "Effects of Air Pollution in Plants", Air Pollution WHO Monograph series 46, Columbia University Press, New York, 233-278, 1961.

"Hydrogen Chloride, of which about 10 ppm for a few hours is required to cause incipient plant damage, was an important pollutant a century ago... (London-Manchester area of England)."

"Guide to Short Term Exposure of the Public to Air Pollutants II. Guide for Hydrogen Chloride", NAS/NRC-1971, National Advisory Center on Toxicology, August, 1971.

This is a well documented short critique of HCl exposure. Based on relatively little evidence they suggest tentative short term public limits of 4 ppm (6 mg/m^3) for 10 min with a public emergency limit of 7 ppm for 10 min, with suitable caveats regarding the need for more research.

Additional references to those cited in ref. 7 of this report include the following:

Linzon, Samuel N. "Effects of Air Pollutants on Vegetation". Introduction to the Scientific Study of Atmospheric Pollution., B. M. McCormac, Editor, D Reidel Publishing Co., Dordrecht-Holland, 1971.

Koga to Taisaku "The Emission Sources of HCl and NH_3 and Their Standard Control Equipment", text in Japanese. (J. Pollution Control) 2 (7) Aug. 1966, p. 461-466.

This study included effects on humans and states, "Ten to fifty ppm HCl does not prohibit work, but is harmful to teeth, nose, mucosa of the mouth and face after long exposure. No one can work in air containing 50-100 ppm HCl.

Taylor, O. C. "Acute Responses of Plants to Aerial Pollutants". Air Pollution Damage to Vegetation, John A. Naegele, editor, Advances in Chemistry Series 122, Am. Chem. Soc., 1973.

This article states that the effect of HCl and Cl is similar to ozone injury. Chloride analysis of plants is not effective since the plant may accumulate chloride through the root system from the soil.

Anon. Data for the Hygienic Evaluation of Hydrochloric Acid Aerosol (Hydrochloride Gas) As an Atmospheric Pollutant. (In: Limits of Allowable Concentrations of Atmospheric Pollutants, Book 6). USSR Literature on Air Pollution and Related Occupational Diseases, Vol. 9, 1962, pp. 18-28.

Extensive data on the effect of HCl on humans recommends that 10 mg/m³ of the aerosol is the limiting maximum allowable concentration.

Heck, W. W., Daives, R. H., and Hinoani, L. J.: Informative Report No. 1, TR-7, Agricultural Committee, APCA, Pittsburgh, Pa., 1970.

A listing of research on the effects of HCl on a number of plants.

Beam, Samuel L. and Wall, Howard Jr. "Atmospheric Emissions for Hydrochloric Acid Manufacturing Processes. Ind. Chem. Div., Allied Chem. Corp., U. S. Public Health Service Publication No. AP-54, 1969.

4.3 INDUSTRIAL EXPERIENCE RELATED TO THE SPACE SHUTTLE PROGRAM

The review of the literature shows that the most stringent standard for ambient air quality is a maximum contamination level of .009 ppm of HCl in Russia. The U.S.A. maximum permissible concentration is 2 ppm for a short period exposure of 1 hr. If we take the latter as the standard to be applied at K.S.C. and environment, we can calculate the amount of air which needs to mix with the cloud to obtain a 2 ppm concentration. This is of the order of approximately 30 km³. The cloud volume measurement made at K.S.C. during the launch of May 20, 1975 indicates a volume of 8 km³ 16 min after launch. The cloud at that time is at an altitude of some 2 km and it has moved approximately 1.6 km from the launch facility. Both elevation and horizontal movement are a function of weather conditions. However, it may be assumed that under normal launch conditions, dilution of HCl in the cloud to 2 ppm or less has taken place before the cloud leaves the K.S.C. area.

The data of May 20, 1975 launch indicate that further dilution of the HCl concentration continues. This dilution is caused by mixing with clean ambient air at the inversion layer. Pictures taken indicate that the cloud is a rather thin stretched-out body, which moves with the wind direction at the inversion layer. If we assume a cloud thickness of 1,200 m, the area of the cloud is of the order of 6.8 km² (2.7 sq miles). It appears that standards set for maximum concentration were met in a period of 15-20 min after launch. The effect on plants as shown in Table VIII implies that the rising cloud with dilution by air will eliminate all potential damage to plant life at K.S.C. and most certainly outside the K.S.C. area.

The above implies that dilution is one way in which the HCl hazard is effectively removed from the cloud. A second way in which the HCl may be removed is by washout. The washout may occur in one of two ways. A sudden thundershower will most likely be of short duration, but rainfall will be heavy. A steady rain will be most likely at a more moderate rate. In order to obtain an indication of the acid concentration, it may be postulated that the HCl will be washed out, starting 20 min after launch by a sudden downpour which deposits .6 cm of rain on the ground. Total amount of water deposited is then:

$$6.8 \times 10^6 \times 10^4 \times .6 = 4 \times 10^{10} \text{ cc} = 4 \times 10^{10} \text{ gr}$$

If all of the HCl washes out, average concentration is then:

$$\frac{16000 \times 10^3}{4 \times 10^{10}} = 4 \times 10^{-4} \text{ gr of HCl per gr of water.}$$

This number is based on the assumption that a Titan vehicle exhausts HCl at the rate of approximately 666 kg/sec. The pH factor of this solution is approximately 2. To get some idea of the acidity of this solution it may be compared to that of some known substances. For instance, vinegar has a pH in the range of 2.4 to 3.4 and lemon juice of 2.2 to 2.4.

5. METHOD OF DELIVERY OF THE NEUTRALIZING AGENT

The existence of a ground cloud and column cloud, together with the assumption that these clouds may not mix very well, leads to the requirement of delivery of neutralizing agent by two separate systems. The ground cloud can be reached from equipment located in the area downstream of the flame trench. The column cloud can only be reached by aircraft after launch of the vehicle at a time primarily determined by safety considerations.

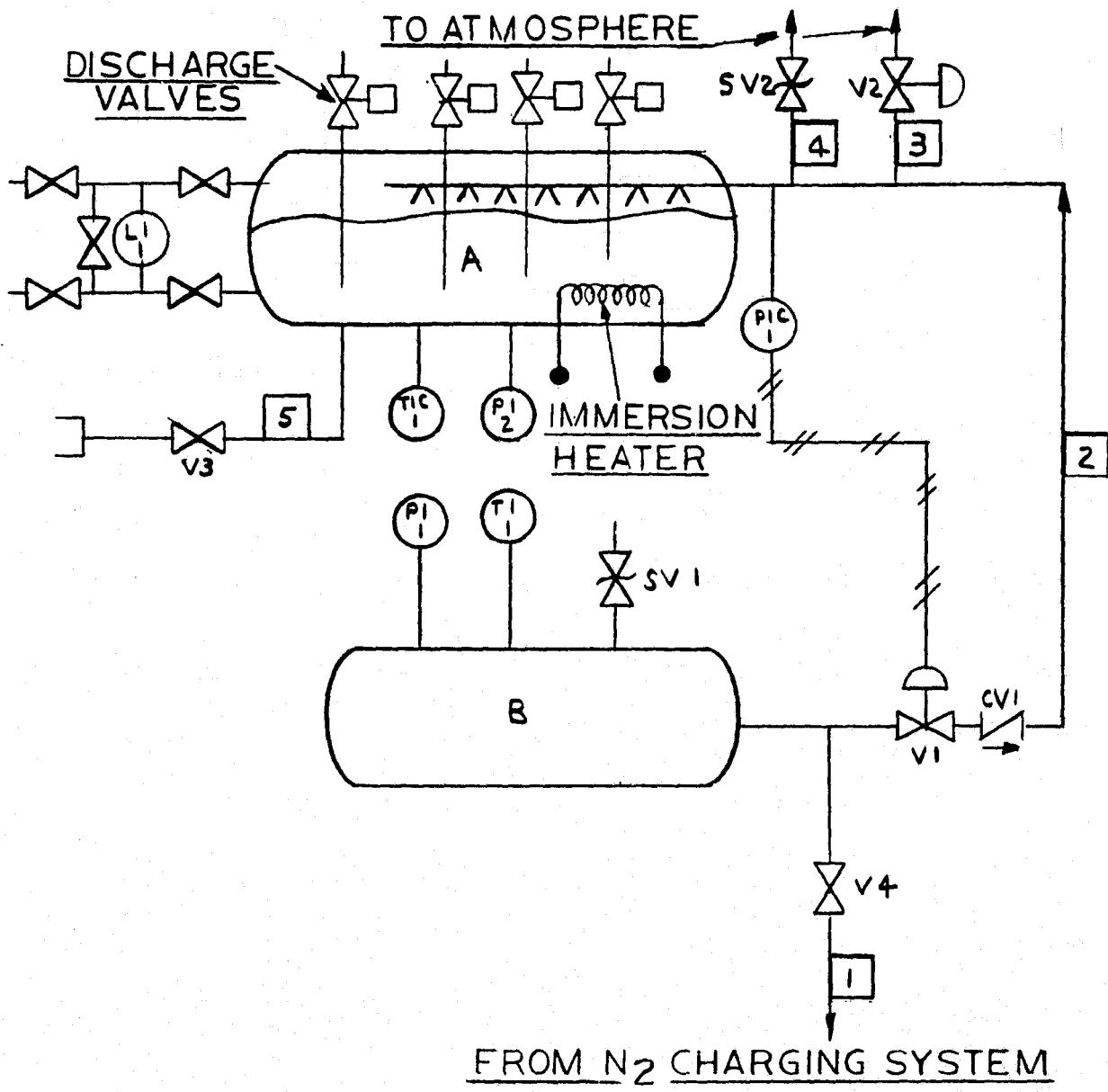
5.1 DELIVERY INTO THE GROUND CLOUD

It seems obvious that the following criteria for ground equipment need to be satisfied:

- a) Delivery needs to be made during the time when the SRM exhaust gases flow through the flame trench.
- b) Mixing of neutralizing agent and the exhaust cloud is solely accomplished through the kinetic energy present in the exhaust plume of the rocket.
- c) Neutralizing agent solution will be vaporized by the hot exhaust gas from the rocket, before dilution of the ground cloud with air reduces its temperature to a point where vaporization becomes impossible.

According to Figure 2.1 there is a large area in which nozzles for the delivery of the aqueous solutions or solids may be located. As discussed in Section 3, it is proposed that the storage equipment of the neutralizing agent solution be located directly in the path of the exhaust plume of the rocket.

Figure 5.1 shows the flow sheet of the delivery system for aqueous neutralizing agent solutions. The solution is delivered by truck and transferred into the storage tank through valve V-3 and line 5. A level gauge LI-1 will indicate the level in the tank. If tank A stores a concentrated mixture, temperature indicator-controller TIC-1 will maintain a preselected temperature through application of electric heat. During storage the pressure in tank A is atmospheric and valve V-2 is open. High pressure gas (air or nitrogen) is stored in reservoir B. The gas has been delivered from a



SCHEMATIC OF AQUEOUS SOLUTION DELIVERY SYSTEM

FIG. 5.1

high pressure manifold or liquid nitrogen pump through a small charge line 1. Valve V-4 will be closed as soon as a sufficient pressure level has been reached.

In order to deliver liquid through the nozzles I of tank A, valve V-1 will be opened. Pressure controller PIC-1 will maintain a preselected pressure above the liquid. To make sure that pressure in tank A is reasonably constant regardless of location, a gas distributor in the tank will be employed. Startup time to reach full flow rate out of the nozzles can be of the order of 1 sec. In that time the ullage space in tank A will be pressurized to the intended value and the column of liquid in the pipes leading to nozzles I accelerated to design value.

Pressure in the tank will be sufficient to:

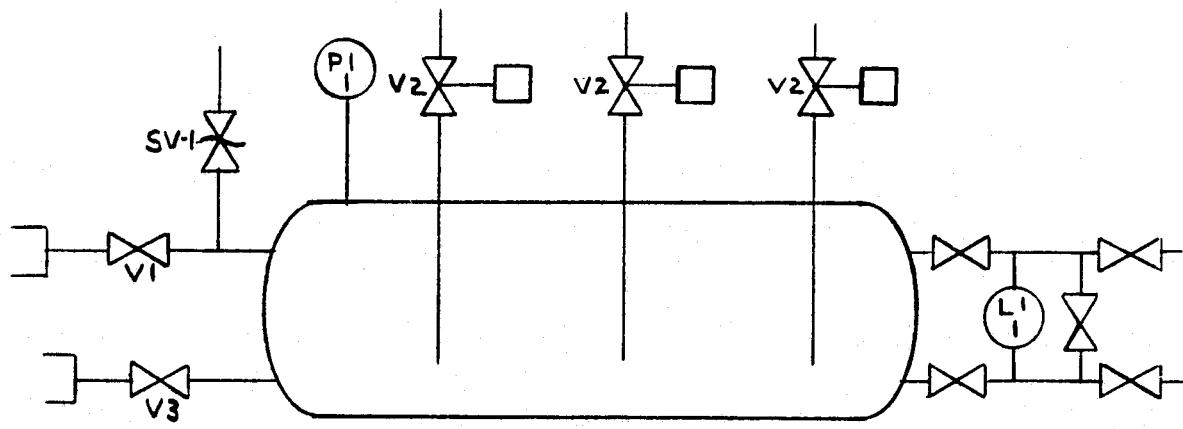
- a) Accelerate the solution to the maximum velocity in the pipes leading to the nozzles.
- b) Overcome pressure from height of column of liquid in the pipe to the nozzle.
- c) Overcome pressure drop in the nozzles.

It is possible to abort the delivery of neutralizing agent by removing the pressure from tank A. This is accomplished by closing valve V-1 and opening V-2. Dependent on size of V-2, delivery may be stopped in a period of 1-3 sec. It is also fairly simple to collect the fluid discharged from the tank by sloping the ground in the area of the tank to a collection point.

The basic system as shown in Figure 5.1 does not change materially (except in size) for the various aqueous solutions discussed in Section 1.

Figure 5.2 shows the flow sheet of the delivery system for NH₃. Since NH₃ at ambient temperature is a liquid under pressure, a pressurization system supplying nitrogen gas is not required. The system operates as follows:

Liquid NH₃ from a transport trailer is delivered and added to the tank through valve V-1. By adding the liquid to the top of the tank, vapor in the tank will be condensed during the transfer operation. The pressure in the tank will be the vapor pressure of the liquid in the tank (Figure 5.3). For delivery of NH₃ to the ground cloud valves V-2 are opened and the NH₃ flows to the nozzles. The flow will be



SCHEMATIC OF NH₃ DELIVERY SYSTEM

FIG. 5.2

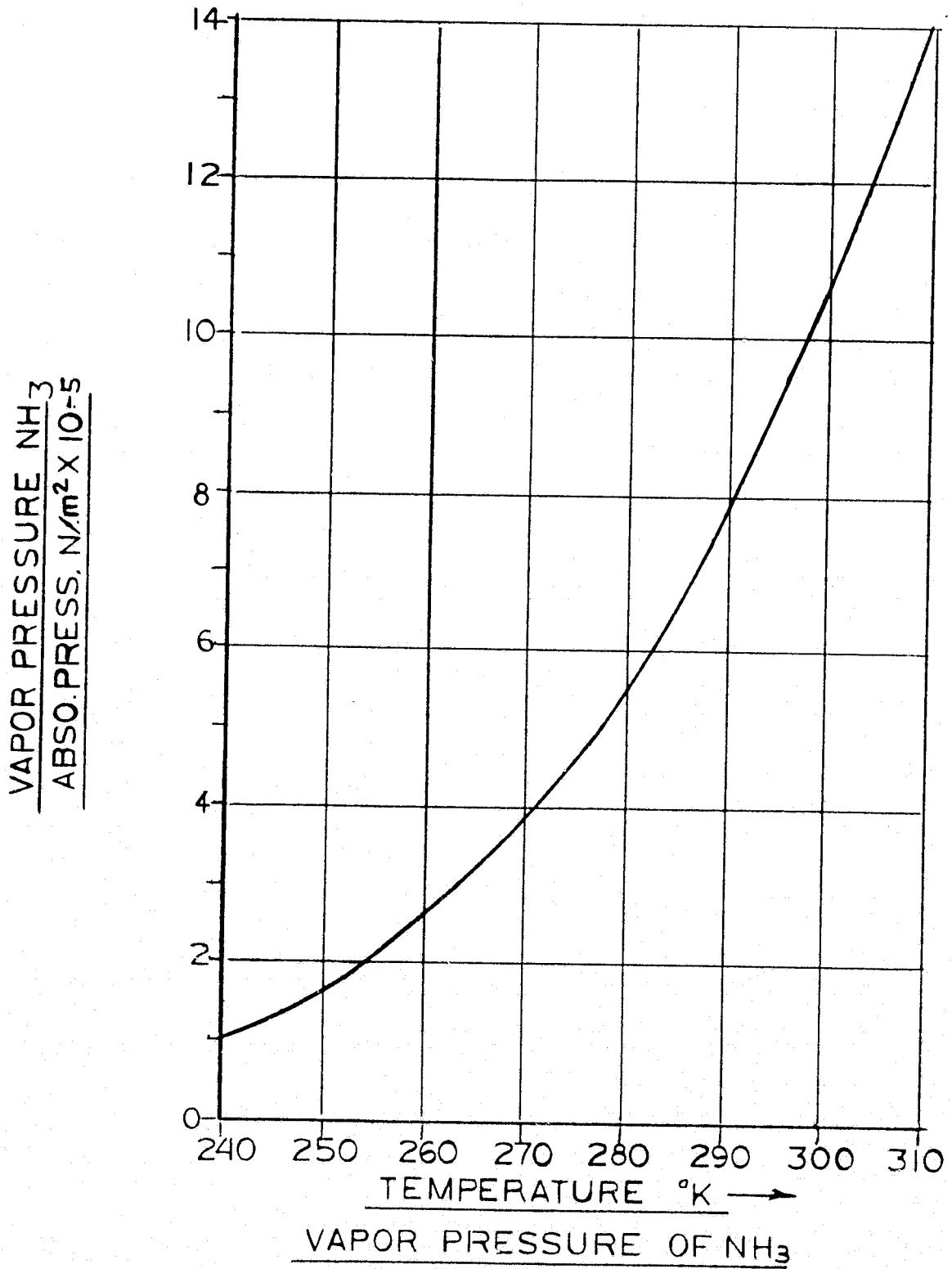


FIG.-5.3

two-phase since pressure in the line to the nozzles drops. Also, the pressure in the tank drops. Figure 5.4 shows the pressure in the tank as a function of liquid contents, assuming a starting pressure of $1.04 \times 10^6 \text{ N/m}^2$ and an initial vapor volume of 10%. The bulk of the liquid NH₃ may be delivered with a pressure decay of the order of $1.5 \times 10^5 \text{ N/m}^2$. Valve V-2 and nozzles need to be sized for two-phase flow. Since most of the pressure drop is taken across the nozzle, the fluid downstream of the nozzle will be a homogeneous mixture of gas and liquid. Liquid fraction in this stream is 79.6% initially at the start of flow and 82% at the end of the discharge cycle. To stop flow from the tank valves V-2 are closed.

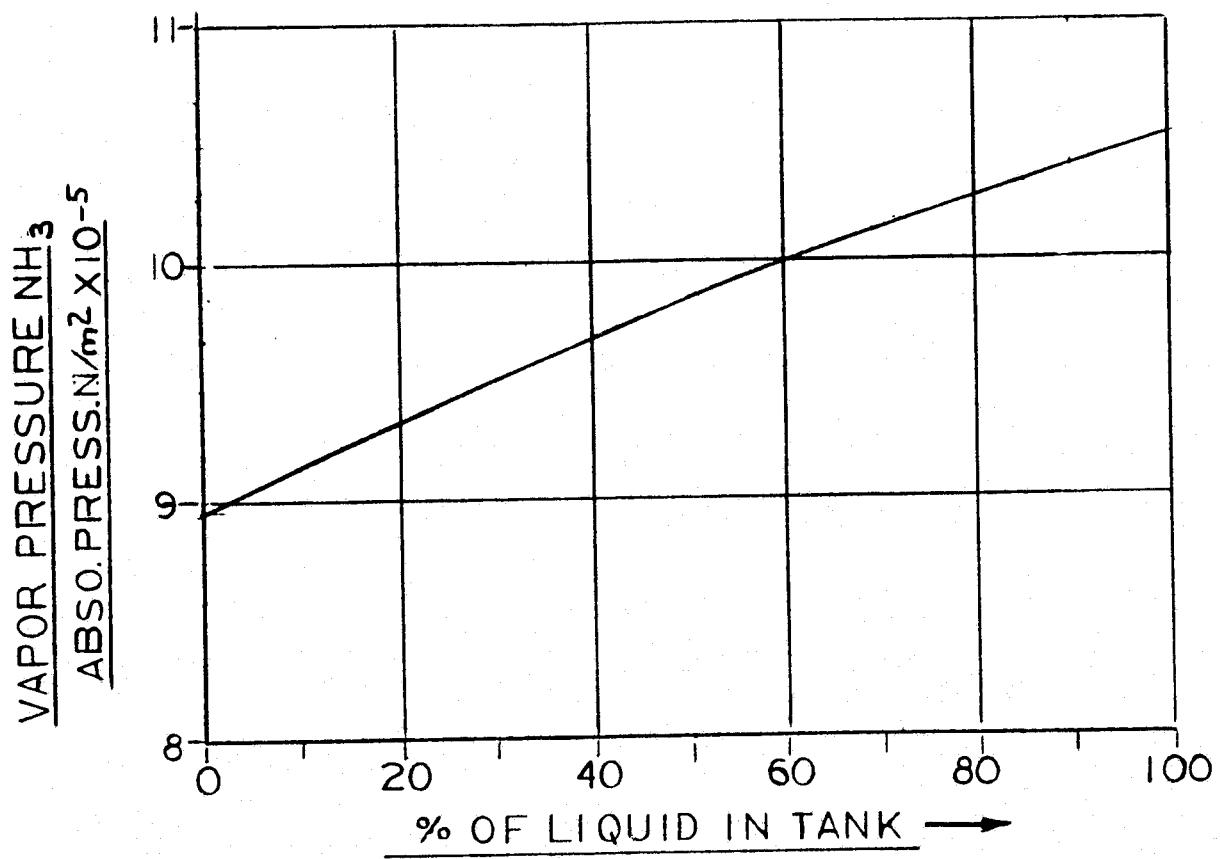
Figure 5.5 shows the flow schematic of a system in which NH₃ may be stored at low pressure and delivered to the ground cloud through pressurization of the vapor space of the tank with nitrogen gas. This system alleviates the major safety hazard associated with NH₃.

The general safety problem consists of two parts as follows:

- a) Bulk liquid is carried at ambient temperature and, therefore, is under pressure. A tank, line or valve failure will release all of the tank contents into the environment.
- b) NH₃ is flammable when mixed in the right proportion with air. Ignition temperature is high and spontaneous ignition does not occur.

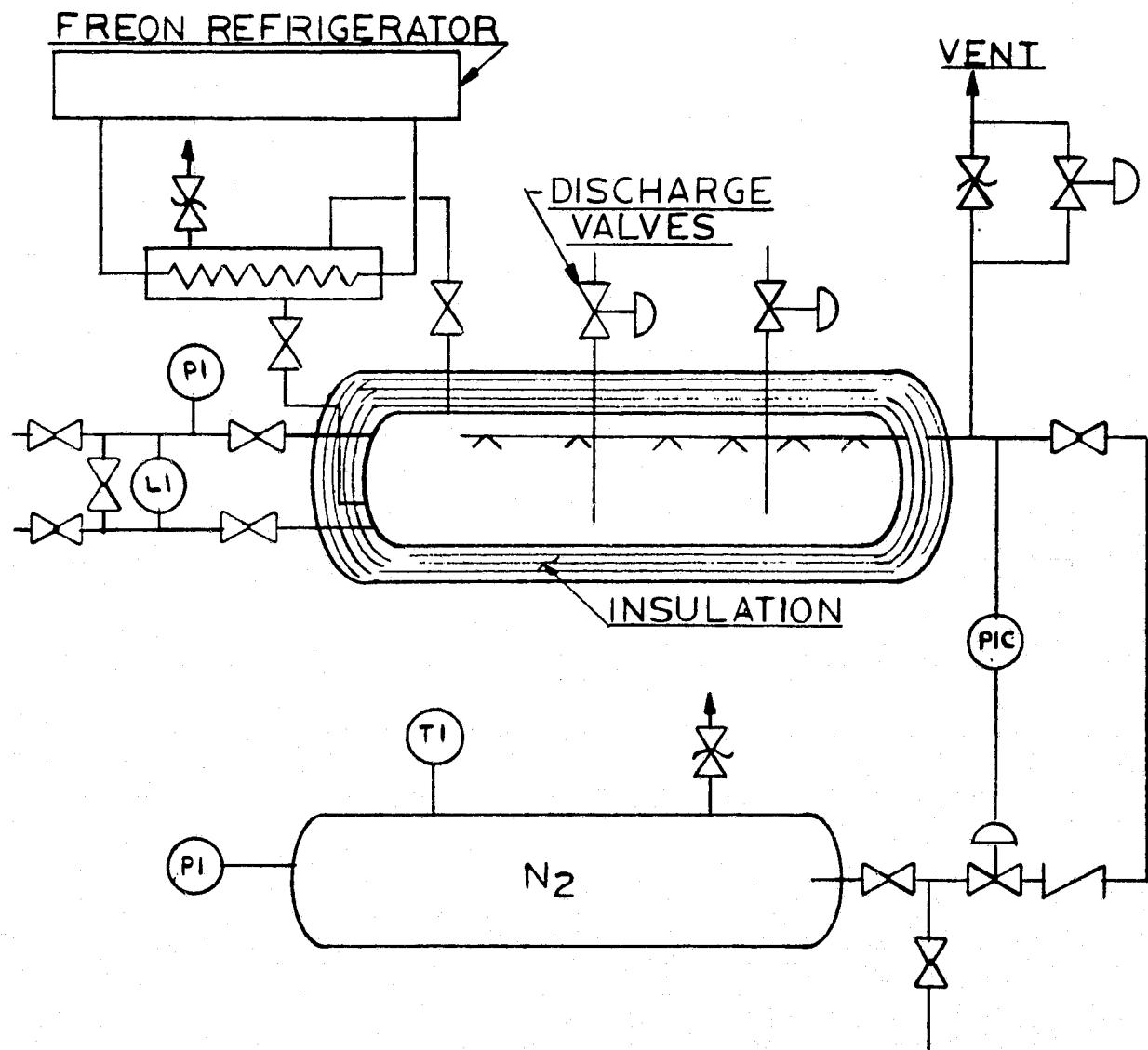
The release of NH₃ at a high rate is by far the most serious problem. It requires evacuation of the area downwind from the leak or spill until the tank is empty or until the leak can be resealed.

It is possible to store the liquid NH₃ at atmospheric pressure in an insulated vessel. Refrigeration is applied in order to maintain the low pressure. The refrigeration cycle to be used can be a simple NH₃ compression system, in which a compressor takes NH₃ vapor of 10^5 N/m^2 and 240°K and compresses it to approximately 10^6 N/m^2 . The compressed gas is then cooled by water and expanded through a valve into the liquid storage vessel. The amount of refrigeration obtained from circulation of NH₃ is of the order of 1,092 J per g of gas circulated. Power required is of the order of 460-575 J/g. A compressor handling 12.6 g/sec of NH₃ gas will need some 7.5 kW and will supply as much as 13,775 W of refrigeration.



PRESSURE IN NH_3 TANK DURING BLOW DOWN

FIG-5.4



LOW PRESSURE NH₃ STORAGE AND DELIVERY SYSTEM

FIG-5.5

An alternate refrigeration system employs a closed cycle freon refrigerator with condenser-evaporator in which NH₃ vapor is continually condensed. This system is shown in Figure 5.5. Operation of the system shown in Figure 5.5 is the same as that of Figure 5.1 with one modification; valves in the lines leading to the nozzles need to be opened to start delivery of ammonia. The system of Figure 5.5 allows pressurization of the vapor space of the NH₃ tank prior to opening of the delivery valves. This insures instantaneous delivery of NH₃. The delivery of NH₃ may also be aborted by closing of the delivery valves. Pressure may be removed from the tank by bleeding nitrogen gas through a remotely controlled bleed valve.

5.2 DELIVERY INTO THE COLUMN CLOUD

The column cloud extends from the ground (initially) to the inversion layer. For this reason, it can be reached only by airborne delivery systems.

The two most likely vehicles to be used for delivery are helicopters or fixed wing aircraft. The most important criteria for delivery are the following:

- a) The neutralizing agent should be minimal in weight and volume to reduce the number of aircraft to be used.
- b) Delivery should be made as soon as is possible after the column cloud has been formed. Mixing of the column cloud with the environment leads to quick dilution and substantial growth of the cloud.
- c) Slow flying aircraft which can dwell in the cloud for relatively long periods are preferred in order to achieve the greatest uniformity of neutralizing agent distribution.

It appears that the greatest problem of any airborne delivery system is the uniform distribution of neutralizing agent. Aircraft are not allowed to enter the cloud until a few minutes after launch. At that time, the cloud is at least a few hundred meters in diameter and approximately 2,000 m high. Wind shear and density difference increase the volume of the cloud quickly. It is impossible for an aircraft or even a number of aircrafts to uniformly cover the volume of the cloud. Consequently, the neutralizing agent needs to disperse itself through the cloud.

When considering the available neutralizing agents, it is clear that NH₃ only meets the requirement of small weight and volume. NH₃ will be carried in a pressurized container aboard the aircraft. When delivering liquid NH₃ from a tank maintained at 26°C and $1.05 \times 10^6 \text{ N/m}^2$ of pressure approximately 21% will vaporize. It is of interest to know the droplet size of the remaining liquid NH₃. Large drops would fall through the column cloud and might reach the ground before complete evaporation takes place. However, the process of nucleation in the expanding stream of NH₃ is such that very fine droplets are formed. The fluid exiting from the nozzles will be a mixture of vapor and small liquid droplets. The volume of the expanded stream is 140 times larger than that of the ambient temperature liquid in the tank. Liquid volume is only 5% of this volume. The density of the cloud of liquid and gaseous NH₃ is 3.8 larger than that of ambient temperature air. As a result the cloud of liquid and gaseous NH₃ will start dropping through the column cloud. During this process air and ammonia will mix, the relative densities of air and the NH₃ cloud will approach each other and liquid NH₃ will vaporize through the addition of heat from the air mixed with the ammonia and the reduction of the partial vapor pressure of the ammonia. It should be noted that without mixing of air with the ammonia cloud no vaporization of the remaining liquid takes place, since the gas environment of the droplets is in thermal equilibrium with the liquid.

An estimate can be made about the rate of decrease in droplet size as a function of heat transfer and settling rate. It appears that droplets of 1 mm in size have a settling velocity of some 3-4 m/sec. At this rate of speed the droplet will vaporize in less than 100 sec. However, it is in existence for a relatively long period of time. It appears that the NH₃ will be spread over a fairly large volume because of the large density difference between air and ammonia and the relatively slow rate of vaporization of the droplets.

6. CONCEPTUAL DESIGN OF GROUND-INSTALLED DELIVERY EQUIPMENT

6.1 TYPES OF DELIVERY SYSTEMS

Basically, five types of ground delivery systems have been analyzed to determine the most likely system for the application. Two of these systems have been found to be impractical from the standpoint of cost and performance when compared to alternate approaches. The systems referred to here are:

a) spray towers with remote storage systems, and b) underground distribution pipes with remote storage tanks. Both of these systems require much more equipment than direct delivery systems and have the added disadvantage of not being able to be deactivated. Section 3.2.1 of this report discusses the nature of the problems associated with systems of this type.

The remaining systems that were investigated are as follows:

- a) Neutralization by introduction of NaHCO_3 and/or Na_2CO_3 in the water system for noise abatement.
- b) Neutralization by direct delivery from underground storage tanks using aqueous solutions.
- c) Neutralization by direct delivery from underground containers using solid neutralizing agents.

6.1.1 Neutralization by the Introduction of Na_2CO_3 in the Water System for Noise Abatement

Since the anticipated water flow rate (9,100 to 18,200 kg/sec) to the pad for noise abatement is nearly identical to that required for neutralization of the ground cloud with Na_2CO_3 solution, it seems natural to utilize this water system to deliver the neutralizing agent. Should the introduction of Na_2CO_3 to pad spray system present no serious problems, the storage tanks could be filled with the Na_2CO_3 solution rather than just water. Since this system will empty completely even if there is an aborted launch, the catch basins at the end of the flame trench will need to be utilized to catch the solution in the event that the launch is aborted. This will require the addition of sufficient curbing at the end of the flame trench to divert the solution into the existing catch basins. Should the mission be aborted, the solution from the catch basins could be recycled back into the storage tanks. No other major modifications are necessary to the system to utilize the Na_2CO_3 solution.

It is assumed that the temperature of the water used in the noise abatement system will be ambient. Under these conditions the solubility of Na_2CO_3 in water is 21.5 g per 100 g of water. Consequently, 25 MT of neutralizer should be added to a minimum of 116.3 MT of water and the total mixture should be delivered over a period of 10 sec. The resulting flow rate would be 14×10^3 kg of solution per sec.

6.1.2 Neutralization by Direct Delivery from Underground Storage Tanks using Aqueous Solutions

For this approach, system requirements were determined for five aqueous neutralizing agents. The system identifications and respective neutralizing agents are as follows:

System A	Sodium Carbonate (Na_2CO_3)
System B	Sodium Bicarbonate (NaHCO_3)
System C	Ammonium Carbonate $(\text{NH}_4)_2\text{CO}_3 \cdot \text{H}_2\text{O}$
System D-1	Ammonia (NH_3) Stored at Ambient Temperature
System D-2	Ammonia (NH_3) Stored at -28°F
System E	Ammonium Hydroxide (NH_4OH)

Table IX provides a summary of the various aqueous delivery systems.

6.1.2.1 Design Criteria. - The criteria for designing the ground delivery systems are in accordance with the following:

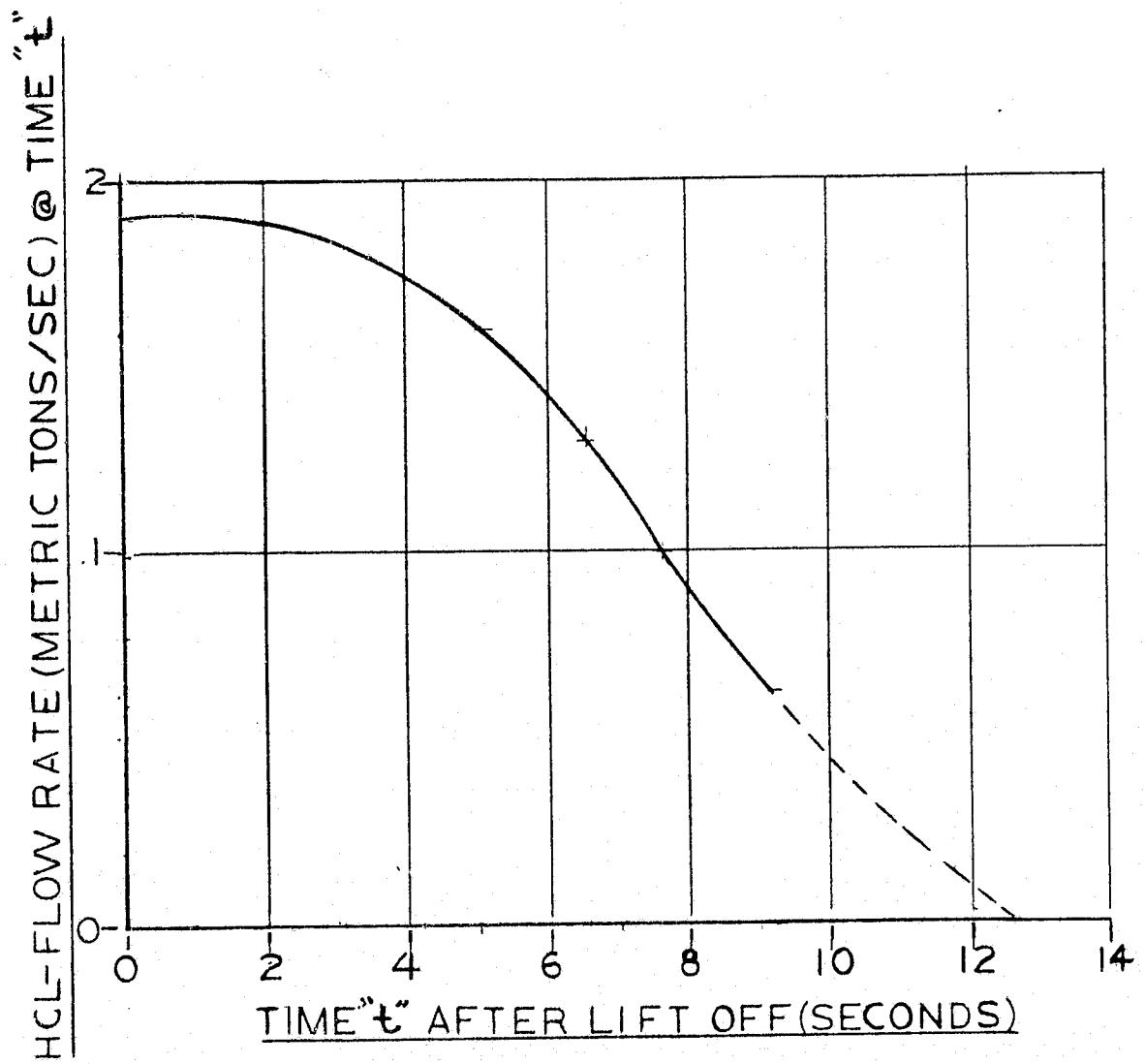
- a) Each of the systems have been sized on the basis of neutralizing only the ground cloud which has been estimated to contain 15.8×10^3 kg of HCl. Figure 6.1 shows the HCl flow rate through the flame trench as a function of time.
- b) The flow rates of the solutions were based on delivering all of the required solution within 10 sec.
- c) In order to provide added neutralization coverage and to compensate for possible losses of neutralizing agent, tank retainage, etc., the amount of solution delivered was increased by 20% over the theoretical requirement.

T A B L E I X

Summary of Aqueous Delivery Systems

Item	SYSTEM A Sodium Carbonate	SYSTEM B Sodium Bicarbonate	SYSTEM C Ammonium Carbonate	SYSTEM D-1 Ammonia	SYSTEM D-2 Ammonia	SYSTEM E Ammonium Hydroxide
1. Size of Storage Tank:	1.52 m dia. x 24.14 m 1g.	2.13 m dia. x 44.5 m 1g.	1.52 m dia. x 10.05 m 1g.	1.06 m dia. x 9.68 m 1g.	1.06 m dia. x 9.68 m 1g.	1.52 m dia. x 13.1 m 1g.
2. Volume - m ³ :	37.85	136.26	14.76	7.19	7.19	19.30
3. Delivery Pres. N/m ² x10 ⁻⁵ Absolute:	2.068	2.068	2.309	6.9-10.3	2.55	1.72
4. Driving Media:	Air or N ₂	Air or N ₂	Air or N ₂	NH ₃ Vapor	N ₂	Air or N ₂
5. High Pres. Tank Vol: ¹	2m ³	6.37 m ³	0.7 m ³	None	0.34 m ³	0.7 m ³
6. Tank Heating Req: ¹	288 x 10 ³ W	900 x 10 ³ W	192 x 10 ³ W	None	None	None
7. Pump Req: ¹	2238 W	7460 W	2238 W	None	None	None
8. Refrigeration Requirements: ¹	None	None	None	None	1.4 x 10 ⁴ J/s	None
9. No. of Dis- charge Noz- zles: ¹	Ten 0.25 m dia.	Twelve 0.50 m dia.	Six 0.25 m dia.	Twelve .076 m ball valves	Twelve 0.10 m ball valves	Six 0.25 m dia.
10. Estimated Cost of System:						
11. Cost of Neu- tralizing Agent/Launch:	\$2,550	\$7,800	\$13,200	\$1,640	\$1,640	\$1,640

¹Quantities specified are per storage tank.



HCL-FLOW RATE THROUGH FLAME
TRENCH DURING LIFT OFF

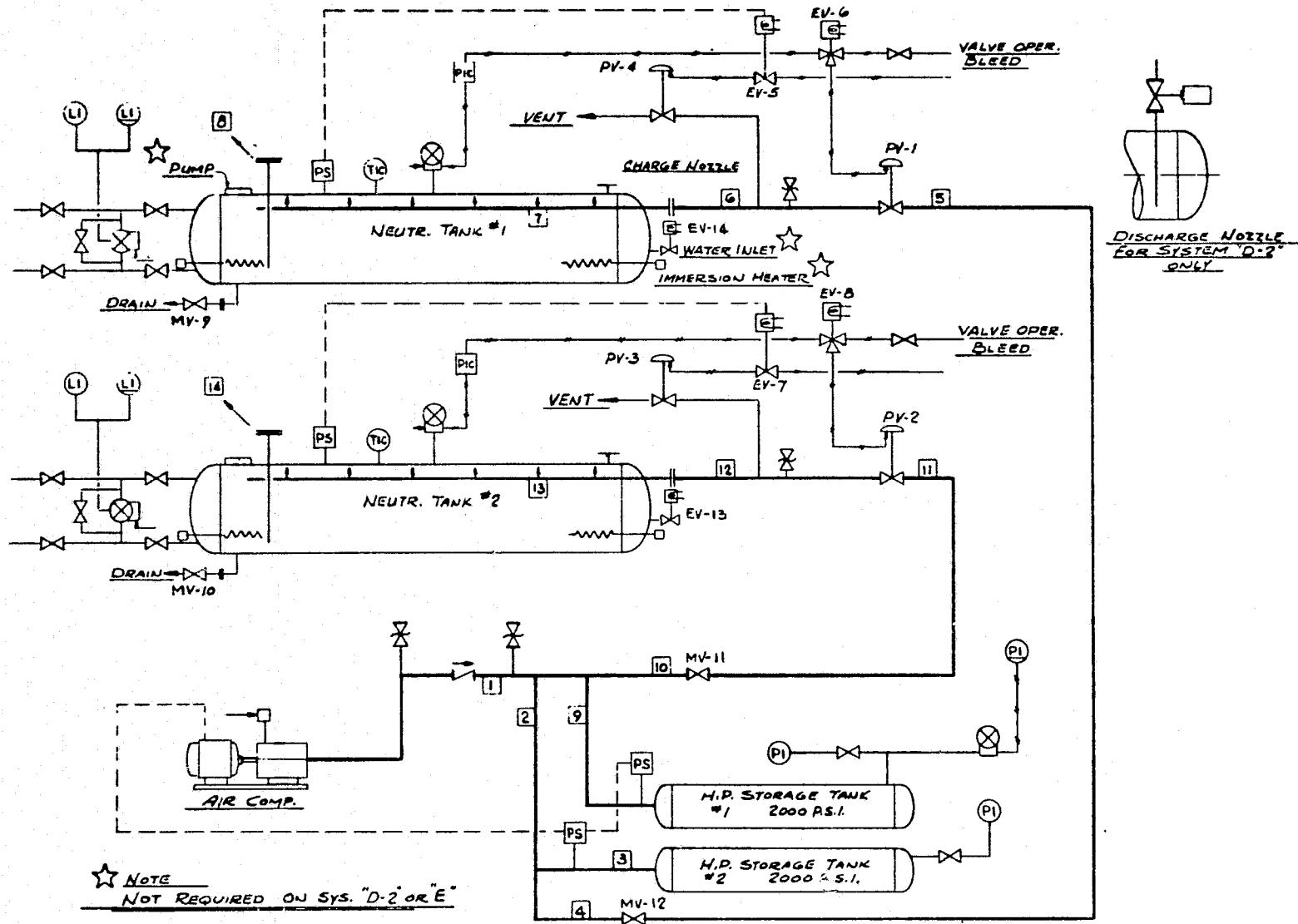
FIG.-6.1

- d) On systems requiring heating, a 6 hr heatup time served as the basis for determining power requirements.
- e) All systems requiring an external driving force were sized on the basis of using a maximum supply pressure of $1.37 \times 10^7 \text{ N/m}^2$ air or nitrogen.
- f) With the exception of Systems D-1 and D-2, the gas flow rates for system activation were established based on a nozzle discharge velocity of 7.62 m/sec.
- g) Dump valves were sized to provide a nominal system deactivation time of 3 sec with the storage tanks half empty and complete air supply shutoff occurring within 3 sec.
- h) Storage tanks were designed in accordance with Section VIII, Division 1 of the ASME Code.
- i) Storage tanks constructed of carbon steel were provided with a $3 \times 10^{-3} \text{ m}$ corrosion allowance.
- j) All storage tanks with the exception of the tanks for Systems D-1 and D-2 were designed for a maximum design pressure of $3.5 \times 10^5 \text{ N/m}^2$.
- k) Storage tanks for Systems D-1 and D-2 were designed for a maximum design pressure of $1.72 \times 10^6 \text{ N/m}^2$.

6.1.2.2 System A - Neutralization by the Introduction of Na_2CO_3 .

System Description: The basic system is shown schematically in Figure 6.2. Two 37.85 m^3 insulated neutralization tanks, a high pressure air storage system and an air compressor are the major components of the system.

Figure 6.3 shows the general outline of the storage tank which serves three functions. The tank serves as a container for mixing the water with the neutralizing agents, a storage vessel and a means of injecting the neutralizer into the exhaust cloud. The tank is provided with a removable 2,238 W, $1.26 \times 10^{-2} \text{ m}^3/\text{s}$ pump which provides the necessary agitation for the solution while it is being heated and charged into the storage tank. Piping inside the tank directs the discharge from the pump into the charging stream of the neutralizing agent as it is being added to water within the tank.



TYPICAL FLOW SHEET
AQUEOUS DELIVERY SYSTEMS A, B, C, D-2 & E

FIG. 6.2

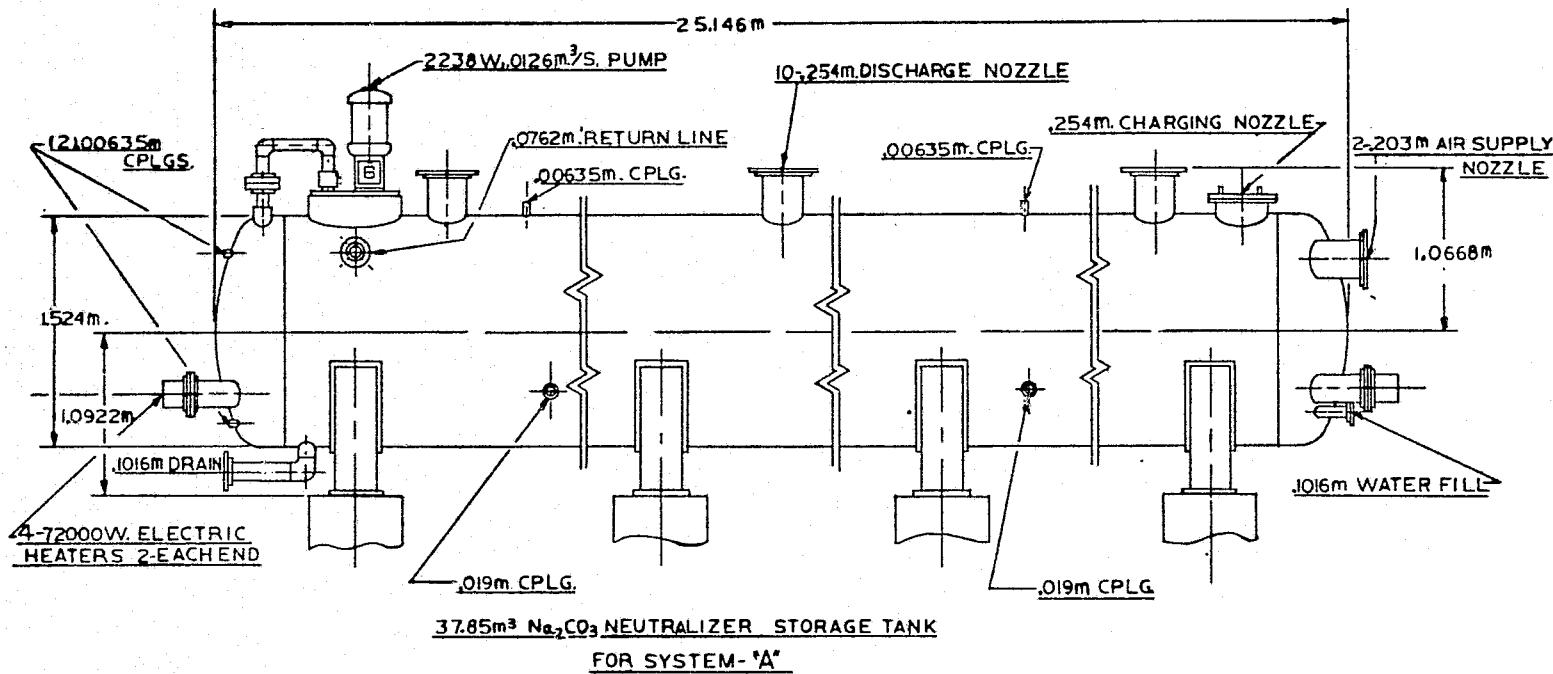


FIG-63

Shortly before the launch, the pump is disconnected externally and removed. A removable cover (not shown) is installed and latched in place sealing the opening. The pump will weigh about 250 kg and requires a lifting device to remove it. If necessary, the same pump can be used for pumping out the pit which houses the storage tank.

Heating is supplied by four 72×10^3 W heaters which are mounted horizontally in the end heads of the tank. These heaters will require approximately 1.5 m of clearance at each end of the tank for removal. The heaters have a watt density of about 6.97×10^4 W/m².

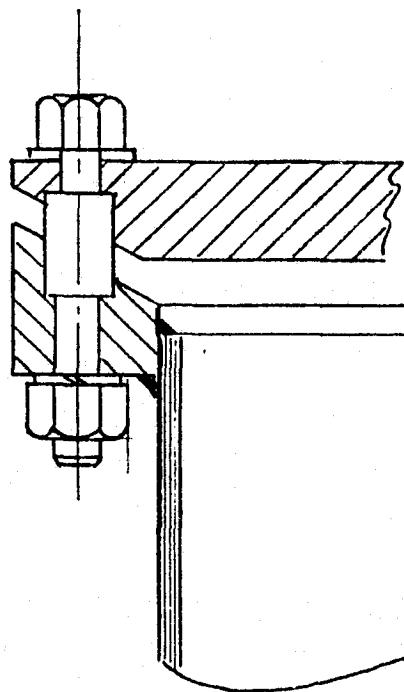
Two .2 m air supply pipe connections are provided at one end of the tank for connection to a remote air supply system. These pipes penetrate the end head and span the entire length of the vessel serving as distribution headers preventing localized cavitation of the neutralizing agent when the system is activated. A .1 m water fill connection is provided to enable filling the tank with the required quantity of water prior to adding the neutralizing agent. The water supply line will be equipped with an automatic valve that will turn off the water supply when the water in the tank reaches the required level. Control of the valve will be accomplished through the use of a differential pressure indicator controller.

For maintenance purposes a .1 m drain valve is provided at the bottom of the tank. If necessary, the tank can be drained into the holding ponds or pumped into tank trucks for temporary storage until maintenance is completed.

Ten 0.254 m diameter discharge nozzles are provided for injecting the neutralizing agent into the path of the exhaust cloud. These nozzles are equipped with pipe extensions which extend to the bottom of the tank permitting almost full utilization of the available neutralizing agent. In operation, a pressure of 2×10^5 N/m² is maintained in the storage tank by the addition of air through the distribution headers, thereby, forcing the solution through the nozzles into the atmosphere. The nozzles consist of two flanges separated by a gap and provided with a tapered annular orifice. Figure 6.4 shows two possible arrangements of the nozzles.

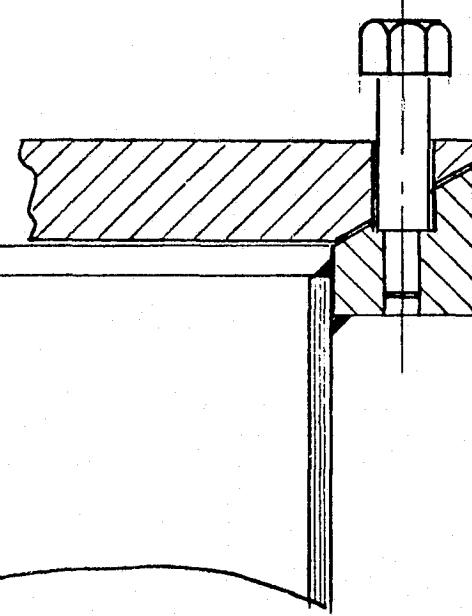
A high pressure storage air supply system is connected to each of the neutralizer storage tanks. The high pressure storage system consists of a 1.37×10^7 N/m² storage tank having a water volume of 1.98 m³. The high pressure tank is located some 15 m away from the storage tank in a protected

FIXED GAP



OPTION #1

LIFTS BY PRESSURE



OPTION #2

DELIVERY NOZZLE DESIGNS FOR
NEUTRALIZATION TANKS

FIG. - 6.4

concrete lined pit. The air supply and dump valves are mounted in the same pit adjacent to the high pressure tanks. The air supply valve requires a C_v of 40 and the dump valves require a C_v of 5,600. Air for the high pressure tanks will be provided by an air compressor which can be located at any convenient location where protection is afforded. The air compressor requirements are $9.4 \times 10^{-3} \text{ m}^3/\text{sec} @ 1.37 \times 10^7 \text{ N/m}^2$. Table X gives the process points for the system along with the required line sizes.

T A B L E X

Process Points for System A (Na_2CO_3 Neutralizing Agent)				
<u>Point</u>	<u>Fluid</u>	<u>Pres. (Abs.)</u> $\text{N/m}^2 \times 10^{-5}$	<u>Flow Rate*</u> $\text{m}^3/\text{sec} \times 10^3$	<u>Line Size</u> $\text{mx} 10^2$
1	Air	137 (max)	9.4	3.34 OD x 2.43 ID
2	Air	137 (max)	4.7	3.34 OD x 2.43 ID
3	Air	137 (max)	7558	8.89 OD x 7.37 ID
4	Air	137 (max)	7558	8.89 OD x 7.37 ID
5	Air	137 (max)	7558	8.89 OD x 7.37 ID
6	Air	2.137	3794 ¹	(2) 21.9 OD x 20.27 ID
7	Air	2.068	189 ²	(40) 11.43 OD x 10.23 ID
8	Na_2CO_3 Sol.	1.013	369.4 ³	27.3 OD x 25.45 ID
9	Air	137 (max)	7558	27.3 OD x 25.45 ID
10	Air	137 (max)	7558	27.3 OD x 25.45 ID
11	Air	137 (max)	7558	27.3 OD x 25.45 ID
12	Air	2.137	3794 ¹	27.3 OD x 25.45 ID
13	Air	2.068	189 ²	27.3 OD x 25.45 ID
14	Na_2CO_3 Sol.	1.013	369.4 ³	27.3 OD x 25.45 ID

*At standard conditions.

¹Flow per each of two 0.2 m pipes.

²Flow per each of forty nozzles.

³Flow per each of ten nozzles.

System Operation: Initially, the tank drain valves are closed and 34 m^3 of water are fed into each of the neutralizer storage tanks by way of the $.1 \text{ m}$ water supply line. When the proper amount of water is in the tanks, the supply valve will automatically turn off. The electric heaters and circulation pump should then be turned on and the temperature of the water allowed to rise to 46°C , as preset on the temperature controller. This will take approximately 4 hrs.

The electric heaters will be staged so that the entire heating load is not instantly applied to the power line. During this time the air compressor can be turned on and the high pressure air storage tanks pressurized to $1.37 \times 10^7 \text{ N/m}^2$. When full pressurization of the tanks is achieved, pressure switches mounted on the tanks will be activated and turn off the compressor. A pressure indicator in the control center will indicate the pressure and verify that the tanks are full. Valves MV-11 and MV-12 will be open as these will only be closed for maintenance purposes.

When the tanks are at the required temperature, the powdered neutralizing agent can be charged into the tanks by way of the 0.254 m charging nozzle provided at the top of the tank. A funnel with a serrated knife edge blade mounted vertically within the funnel will facilitate the charging operation in the event that bags of neutralizing agent rather than bulk materials are used. The bags may simply be dropped on the knife edge and the blade will rupture the bags depositing the material into the tank. It will be necessary to charge each tank with 13.4 MT of material. Approximately 2 hrs of additional heating time will be required to bring the solution up to 46°C . Following the charging operation, the charging cover will be closed and secured. At this point, the three-way solenoid valves, EV-6 and EV-8, are unloading the air supply valves, PV-1 and PV-2, and no air is being supplied to the tanks. The air dump valve is closed since the pressure in the tank is below the set point of the pressure switches on the storage tanks. The pressure controller is then set for $2.07 \times 10^5 \text{ N/m}^2$ absolute. The heaters will be turned off.

The system will be activated from the control center in accordance with a preestablished timing sequence. At the time of activation solenoid valves EV-6 and EV-8 will be energized and the pressure controller will supply the necessary operating pressure to open air supply valves PV-1 and PV-2. Air flowing through the distribution headers will provide the necessary driving force to deliver the neutralizing solution into the path of the oncoming exhaust cloud. Approximately 1 sec will be required for the solution to begin discharging.

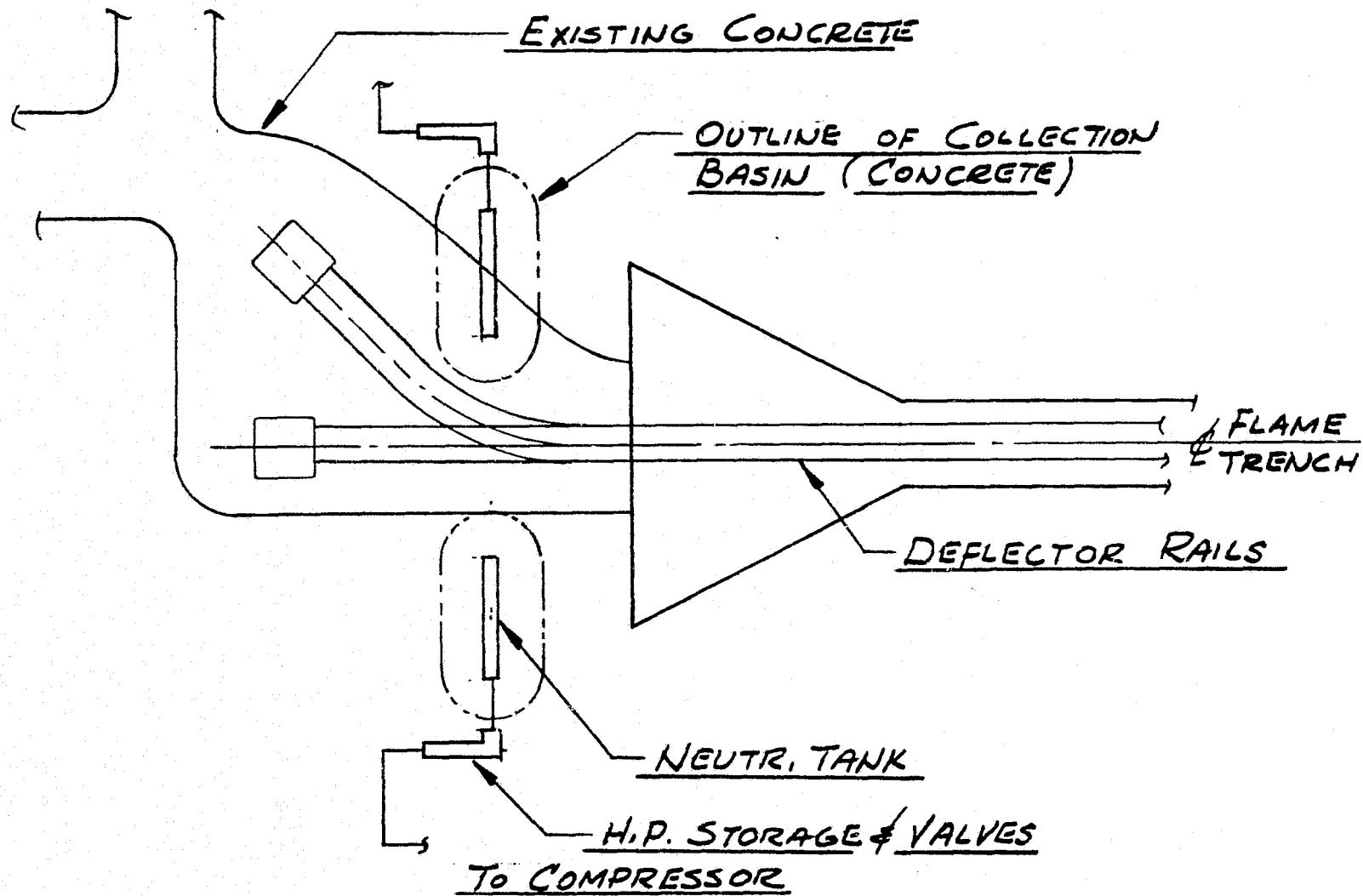
When the tanks are empty the liquid level controllers will signal solenoid valves EV-6 and EV-8 to bleed off the air from the valve operators of PV-1 and PV-2, closing the air supply valves within a period of 3 sec.

Should the system be accidentally activated, the neutralizing solution will discharge and continue to do so until an abort signal is supplied to valves EV-5, EV-6, EV-7 and EV-8. At this point, the air supply valves will begin closing and the air dump valve will open. Within approximately 3 sec, the air pressure keeping the supply valves open will have been bled off through the bleed valves connected to solenoid valves EV-6 and EV-8 and the supply valve will be closed. Concurrently, the air pressure in the storage tanks will have been released through the dump valve and the flow of the neutralizer stopped. The material that has been discharged will be returned to the pits that house the storage tanks by way of a sloping 12.2 m wide concrete apron that surrounds the pit of the tanks. The pits are equipped with sumps and mounting facilities for installing a pump for returning the solution back to the storage tanks.

Installation: The neutralizing tanks and the high pressure storage systems will be installed below grade in concrete-lined pits. The location of these components relative to the flame trench is shown in Figure 6.5. As can be seen from the figure, the neutralizer tanks are located downstream of the flame trench directly in the path of the exhaust gases which pass through the trench. The high pressure storage systems are located east and west of the neutralizer tanks, a distance of some 15 m.

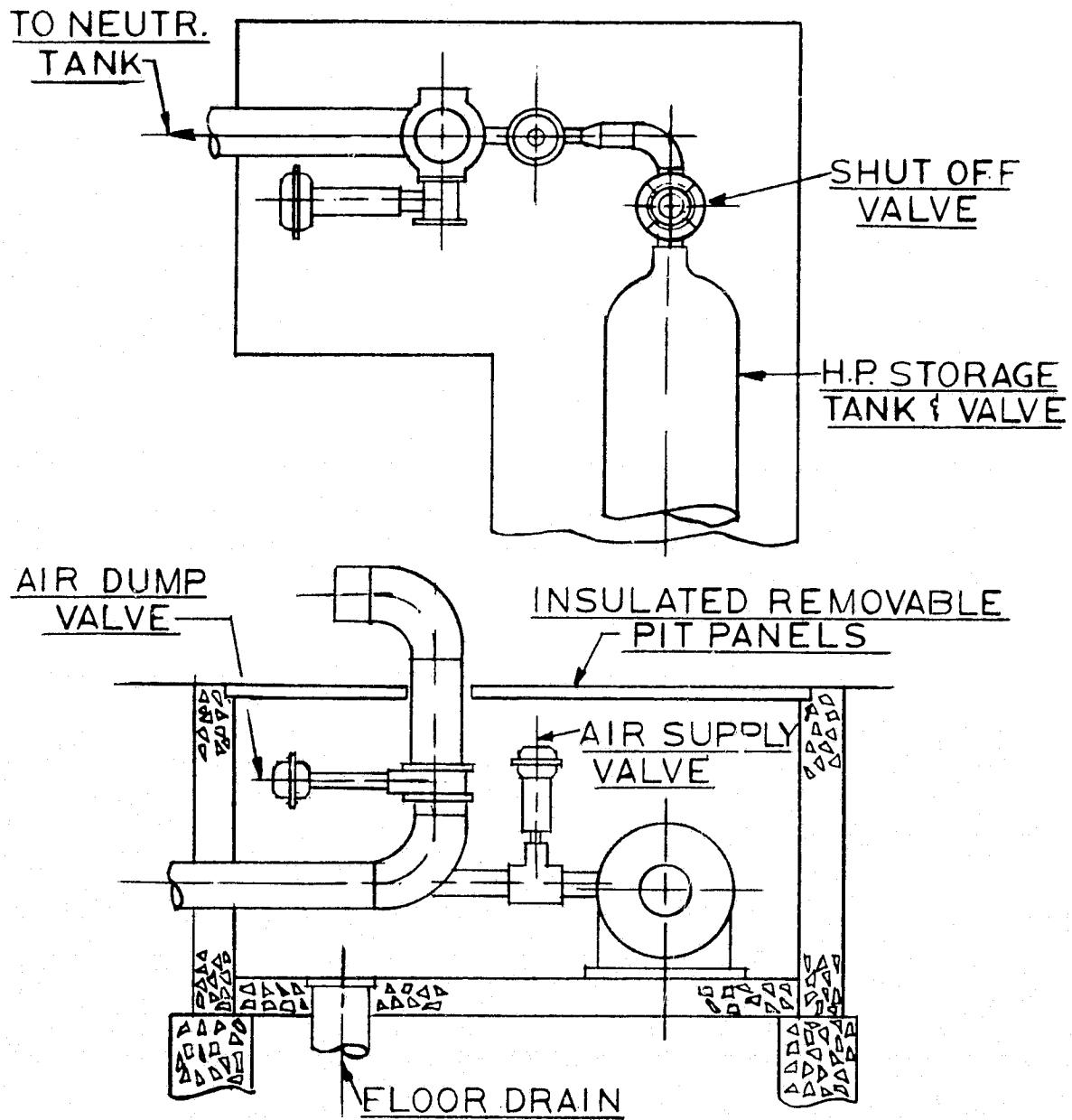
Figure 6.6 shows the installation scheme for the high pressure storage system. The equipment is mounted in a concrete pit covered with removable panels, filled with a high temperature insulating material. The panels consist of structural frames covered by steel plates to provide weather protection. The underside of the frames are covered with perforated sheets and the insulation is sandwiched between the top and bottom covers. The air dump valve, a pneumatically-operated butterfly valve, is ported through the insulating panels and discharges in a northerly direction. The high pressure tank and valving are piped directly to a 0.3 m underground pipe which connects to the neutralizing tank pipe headers. A floor drain or other means of draining the pit must also be provided.

The installation of the neutralizer tanks is shown in Figure 6.7. A concrete-lined pit, 30 m long by 2.74 m wide by 2.53 m deep, must be provided to accommodate the tank.



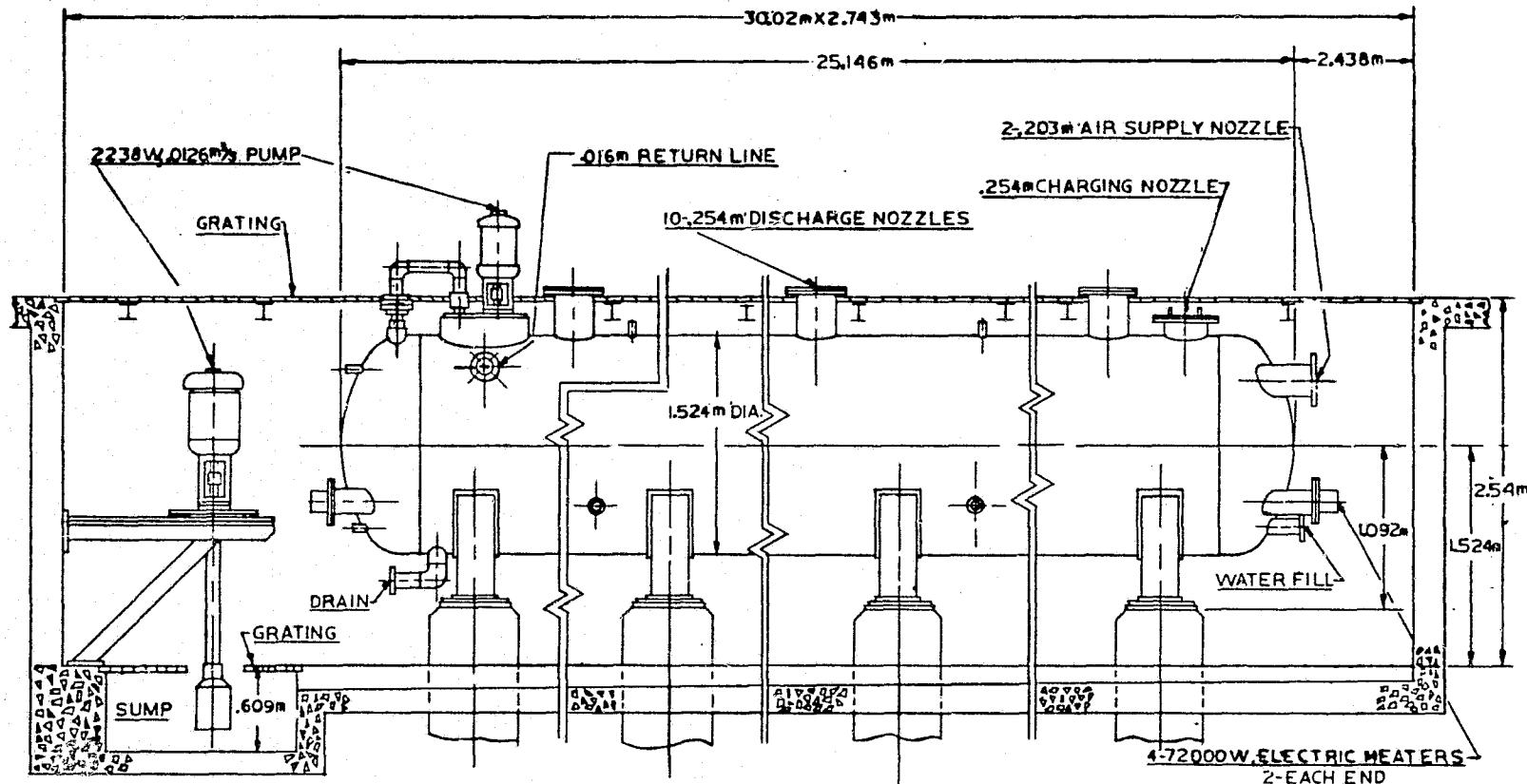
PLAN VIEW OF NEUTRALIZATION SYSTEMS

FIG. 6.5



TYP. INSTALLATION OF HIGH PRESSURE
STORAGE SYSTEM

FIG.6.6



INSTALLATION OF Na_2CO_3 NEUTRALIZER STORAGE TANK IN PIT

FIG-6.7

The floor of the pit slopes toward one side providing drainage into a trench running the length of the pit. A sump is provided at one end of the pit along with a pump mounting bracket and a removable pump to collect and return unused neutralizing agent to the tank. The pumping system could also be used to remove rain water from the trench if elevations do not permit drainage. Surrounding the top of the pit is a 12.2 m wide concrete pad, sloped to provide drainage into the pit. The top of the pit is covered with removable floor grating which is anchored to structural supports spanning the width of the pit.

The neutralizing tanks are shop-fabricated items. The tanks can be shipped to the site completely fabricated, ready for installation. In order to accommodate the tanks, four concrete piers will be required within each pit. The reactions for the center supports will be in the order of 21.77×10^3 kg each and the reactions of the end supports will be 8.16×10^3 kg each. The tank will be sufficiently elevated within the pit to permit holding all of the neutralizing agent at a level well below the tank. The saddle support at the charging end of the tank will be a "fixed" support, bolted firmly to its support pedestal. The remainder of the supports will be "sliding" supports to allow for expansion and contraction of the tank during heatup and cooldown.

Since the neutralizing agent requires heating, it will be necessary to insulate the tank. This is best accomplished in the field and will require covering the tank with a 5×10^{-2} m blanket insulation, such as mineral fiber, in addition to a 1.27×10^{-2} m thick plaster coat and a weatherproofing sealer. The estimated temperature in the pit area during launch is 600°K and, consequently, all vessel attachments, such as heaters, electrical cables, instrument sensors and transmitters, will require protection of the same nature. Items, such as power disconnects, control line solenoids and bleed valves, will be installed in the high pressure system pit and will be weatherproofed.

6.1.2.3 System B - Neutralization by the Introduction of NaHCO_3 .

System Description: System B is the largest system of all the systems analyzed. The storage tanks have a volume 3.6 times that of System A, and heating, pumping and flow rates are correspondingly larger. The system is shown schematically in Figure 6.2. As can be seen from the figure, the system requires the same major components as System A. Because System B appears to offer no advantages and does have many disadvantages over A, only data essential to providing

relative comparison has been provided. A tank drawing is not included in the report, however, it may be described as a tank 2.13 m in diameter by 44.5 m long.

Additional description of the system would be identical to System A with the following exceptions:

- a) A 7,460 W pump would be required.
- b) Six 150×10^3 W heaters would be required.
- c) 1.83 m of clearance would be required for removal of heaters.
- d) Twelve 0.5 m diameter discharge nozzles would be required.
- e) The high pressure storage system would require a water volume of 6.37 m³.
- f) The C_v for the air supply valve would be 150.
- g) The C_v for the air dump valve would be 20,000.

System Operation: The operation of System B would be identical to System A, except that the quantity of water required for each tank would be 136 m³ and the amount of neutralizing agent would be 15.5 MT.

Installation: The installation requirements for System B would be identical to System A with the following exceptions:

- a) The high pressure tank and valving would be piped to a 0.5 m underground pipe for connection to the neutralizing tank pipe headers.
- b) The pits for the neutralizer tanks would be 49.4 m long by 3.35 m wide by 3.15 m deep.
- c) The tanks would be only partially shop-fabricated, perhaps in two sections, then field-welded together.
- d) The saddle support reactions would be different, depending on the number of supports used.

6.1.2.4 System C - Neutralization by the Introduction of $(\text{NH}_4)_2\text{CO}_3\cdot\text{H}_2\text{O}$.

System Description: System C is the smallest of the carbonate systems. Figure 6.2 is again applicable as the schematic flow diagram of the system. The major components are the same as for System A and only differ in size. Figure 6.8 shows the neutralizer storage tank for System C. Further description of the system is identical to System A with the following exceptions:

- a) The neutralizer storage tanks have a capacity of 14.76 m^3 .
- b) Heating is supplied by four $48 \times 10^3 \text{ W}$ heaters.
- c) Two 0.15 m air supply connections are provided.
- d) Six 0.254 m diameter discharge nozzles are provided.
- e) The pressure to be maintained in the tanks is $2.34 \times 10^5 \text{ N/m}^2$ absolute.
- f) A water volume of 0.7 m^3 is required for each of the high pressure storage systems.
- g) The air supply valve requires a C_v of 20.
- h) The air dump valves requires a C_v of 2,000.
- i) Table XI gives the process points for the system along with the required line sizes.

System Operation: The operation of System C will be identical to that of System A, except that the 14.76 m^3 of water and 14.65 MT of neutralizing agent are required for each tank. In addition, it will be necessary to set the pressure controller for $2.34 \times 10^5 \text{ N/m}^2$.

Installation: The installation of the delivery system is basically identical to System A. The differences are:

- a) The high pressure tanks and valving are piped to a $.254 \text{ m}$ pipe which connects to the neutralizer tanks.
- b) Figure 6.7 is applicable, except that the pit dimensions will be 14.93 m long by 2.74 m wide by 2.54 m deep and only two pedestals will be required.
- c) The support reactions will each be $16.55 \times 10^3 \text{ kg}$.

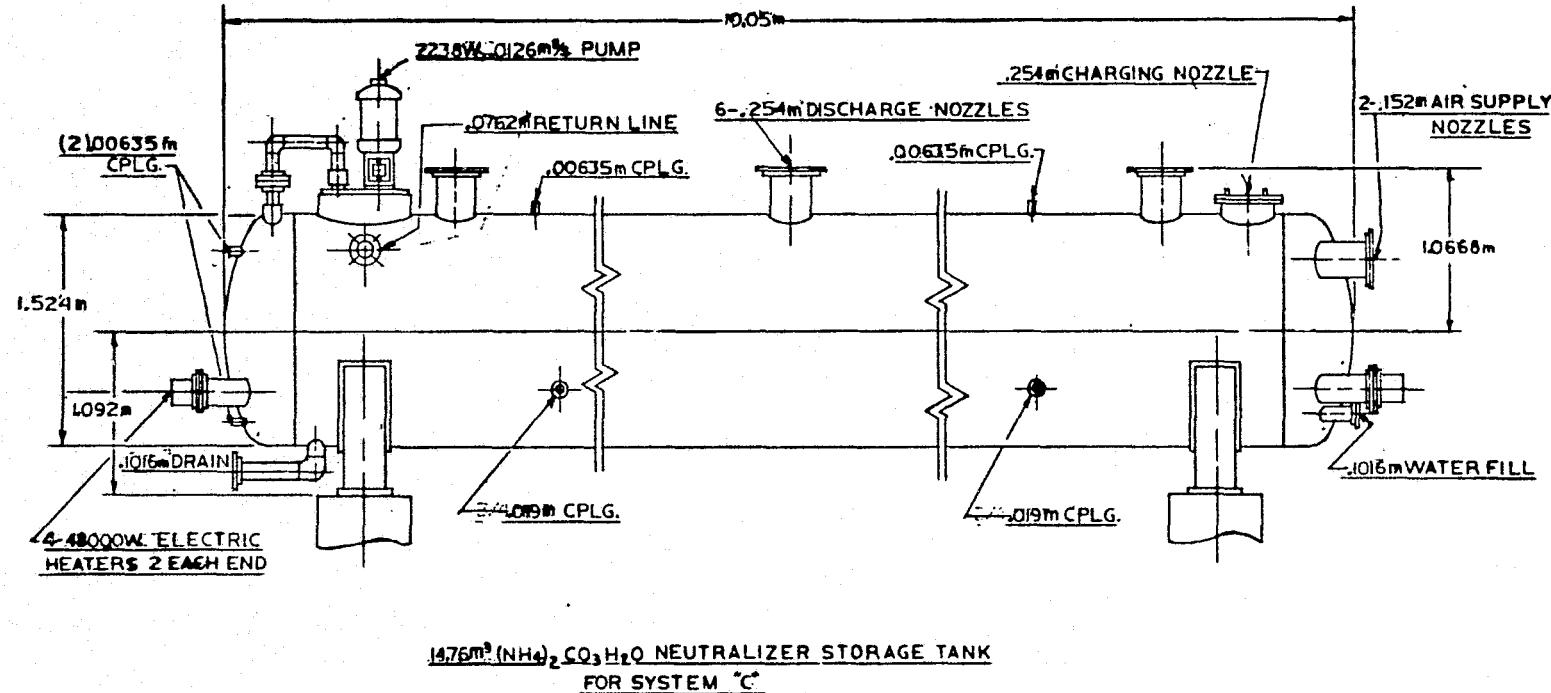


FIG-68

T A B L E X I

Process Points for System C
(Ammonium Carbonate Neutralizing Agent)

Point	Fluid	Pres. (Abs.) N/m ² x 10 ⁻⁵	Flow Rate* m ³ /s x 10 ³	Line Size m x 10 ²
1	Air	137 (max)	9.4	3.34 OD x 2.43 ID
2	Air	137 (max)	4.7	3.34 OD x 2.43 ID
3	Air	137 (max)	3340	6.03 OD x 4.92 ID
4	Air	137 (max)	3340	6.03 OD x 4.92 ID
5	Air	137 (max)	3340	6.03 OD x 4.92 ID
6	Air	2.309	1670 ¹	16.82 OD x 15.40 ID
7	Air	2.295	167 ²	11.43 OD x 10.23 ID
8	(NH ₄) ₂ CO ₃ . H ₂ O	1.013	243 ³	27.3 OD x 25.45 ID
9	Air	137 (max)	3340	27.3 OD x 25.45 ID
10	Air	137 (max)	3340	27.3 OD x 25.45 ID
11	Air	137 (max)	3340	27.3 OD x 25.45 ID
12	Air	2.309	1670 ¹	27.3 OD x 25.45 ID
13	Air	2.295	167 ²	27.3 OD x 25.45 ID
14	(NH ₄) ₂ CO ₃ . H ₂ O	1.013	243 ³	27.3 OD x 25.45 ID

* At standard conditions.

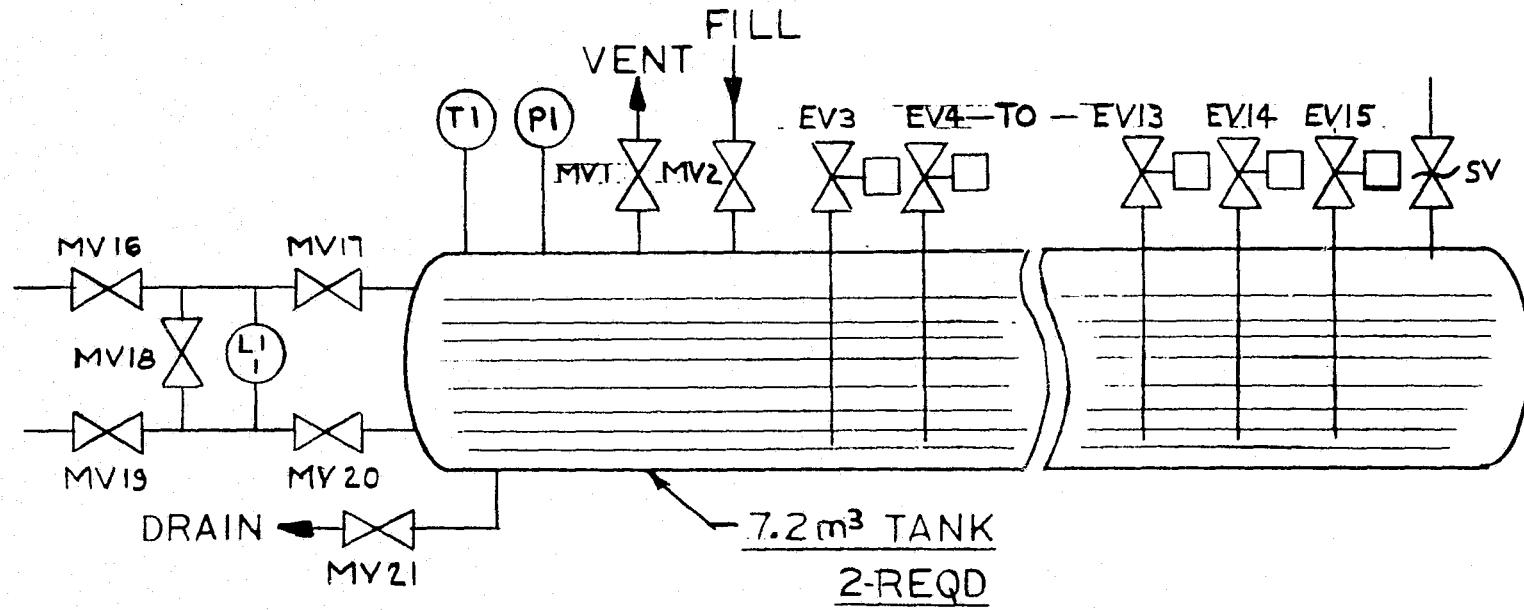
¹ Flow for each of two 0.152 m lines.

² Flow for each of twenty 0.1 m nozzles.

³ Flow per each of six nozzles.

6.1.2.5 System D-1 - Neutralization by the Introduction of NH₃ Stored at Ambient Temperature.-

Description of System: System D-1 differs from all the previous systems in several ways. It does not require an external driving force, a circulation pump or heaters, and the discharge nozzles consist of a series of electrically-operated ball valves. The flow sheet of the system is shown in Figure 6.9.



SCHEMATIC OF NH₃ DELIVERY SYSTEM
STORED AT AMBIENT TEMPERATURE

SYSTEM D-1

FIG-6.9

Two 7.2 m³ storage tanks constructed of Type 316¹ stainless steel having a pressure rating of 1.72×10^6 N/m² are required. The outline of these tanks is shown in Figure 6.10. The tanks are each equipped with twelve 0.0762 m ball valves which serve as the discharge nozzles. As in the case of previous systems, the pipe nozzles extend to the bottom of the tank to provide full utilization of the neutralization agent. Two 0.0762 m ports are provided to facilitate filling the tank. In addition, instrument taps are provided for purposes of pressure and temperature readout and liquid level control. The 0.1 m drain connection shown in Figure 6.10 is provided to facilitate shop testing of the tank. The tanks are relatively small and, as such, can be completely shop-fabricated and delivered to the site ready for installation. The tank itself need not be insulated as it will be operating at ambient temperature in a pit protected from the high temperature exhaust gases of the rocket.

System Operation: Initially, all discharge valves are closed and fill and vent connections are made to a tank truck containing liquid NH₃ at ambient temperature. Depending on the temperature of the liquid, the pressure in the tank truck will be in the range of 6.89×10^5 N/m² to 9.65×10^5 N/m² (for a temperature range of 12°C to 23°C). The valves on the vent line will be opened and the pressures in the tank truck and the neutralization tank will be allowed to equalize. The valves on the fill line will then be opened and the remainder of the NH₃ will be emptied into the storage tank. Since each tank requires only 7.2 m³ of NH₃, only one tank truck will be required to fill both storage tanks. The process of equalizing pressures and filling with liquid will be the same for both.

When the storage tank is filled with the required amount of liquid, the system is ready for activation. The vapor pressure of the liquid will again be a function of the temperature of the liquid. The system will be activated by powering the electric operators on the ball valves. As the valves begin to open, the vapor pressure of the liquid will drive the NH₃ through the discharge nozzle exiting at sonic velocity. The system will continue to discharge ammonia until the vapor pressure in the tank reaches atmospheric pressure. At this point, the tank will be empty. The system can be stopped by closing the ball valves, however, no reclamation of the discharged NH₃ will be possible.

¹Stainless steel has been specified for purposes of process condition requirements and estimating purposes, however, the choice of materials may require further consideration since the chlorides from the seawater are present and may lead to stress corrosion cracking.

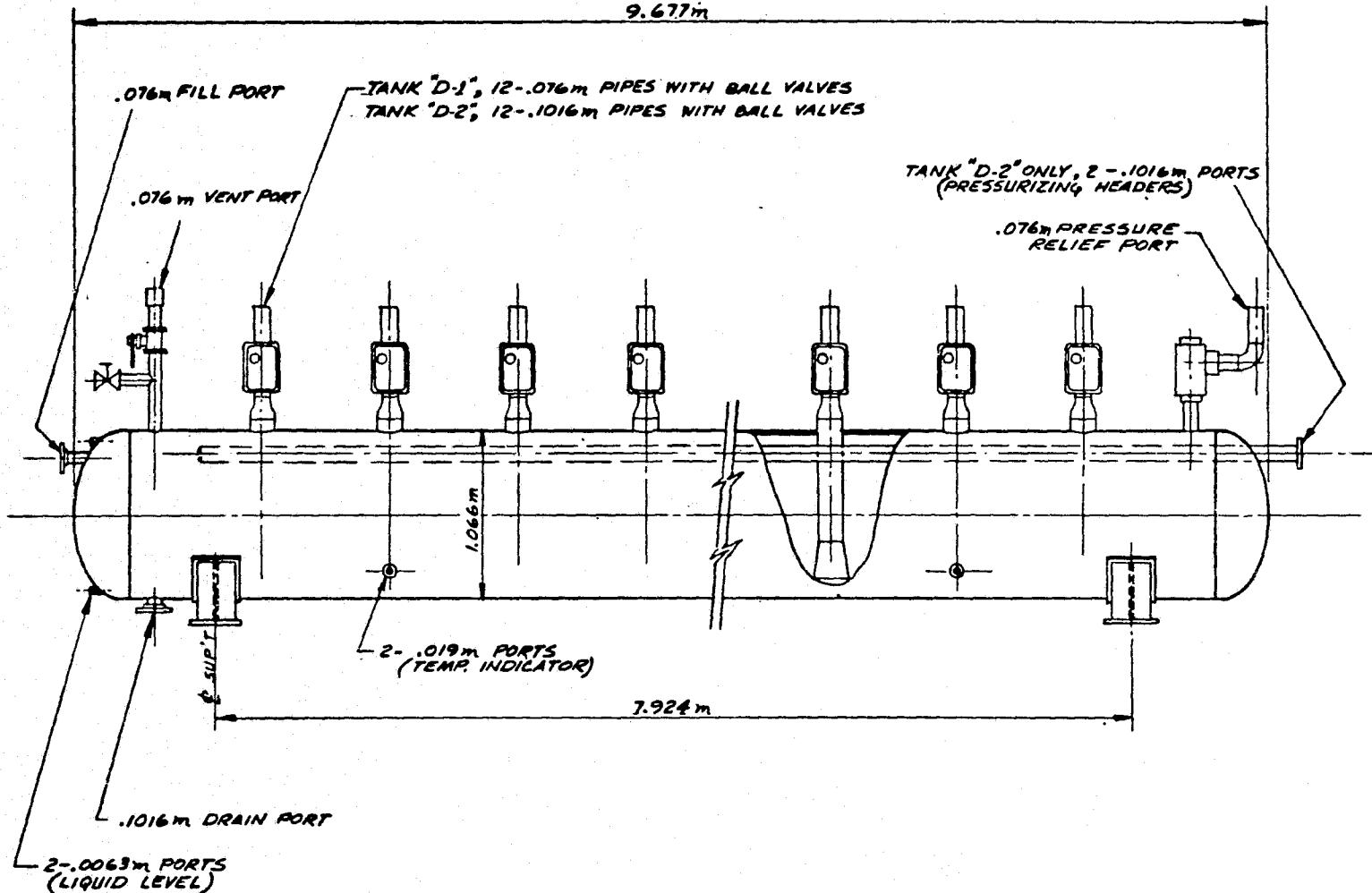


FIG -6.10

Installation: The installation of the ammonia systems differ somewhat from the previous types of installations. Figure 6.11 shows the installation of a storage tank. Aside from the elimination of an air supply system, the installation differs from the carbonate systems in one major way. Instead of covering the top of the pit with floor grating, a series of removable insulated panels are used.¹ The insulated panels provide the necessary protection for the valves, controls and instrumentation and other equipment installed in the pit. In order to minimize drainage of rain water into the pit, the concrete pad surrounding the pit should be provided with drain gutters or be sloped away from the pit in all directions. As with other systems, a sump pump can be provided in the pit for removal of drain water.

No threaded connections should be made to the vessel. Preferably, all connections should be welded or, if mechanically joined, must be suitably sealed with O-rings to prevent leakage of the NH₃ gas. Underwriters Lab classifies NH₃ as a Group 2 toxic gas which is defined as follows:

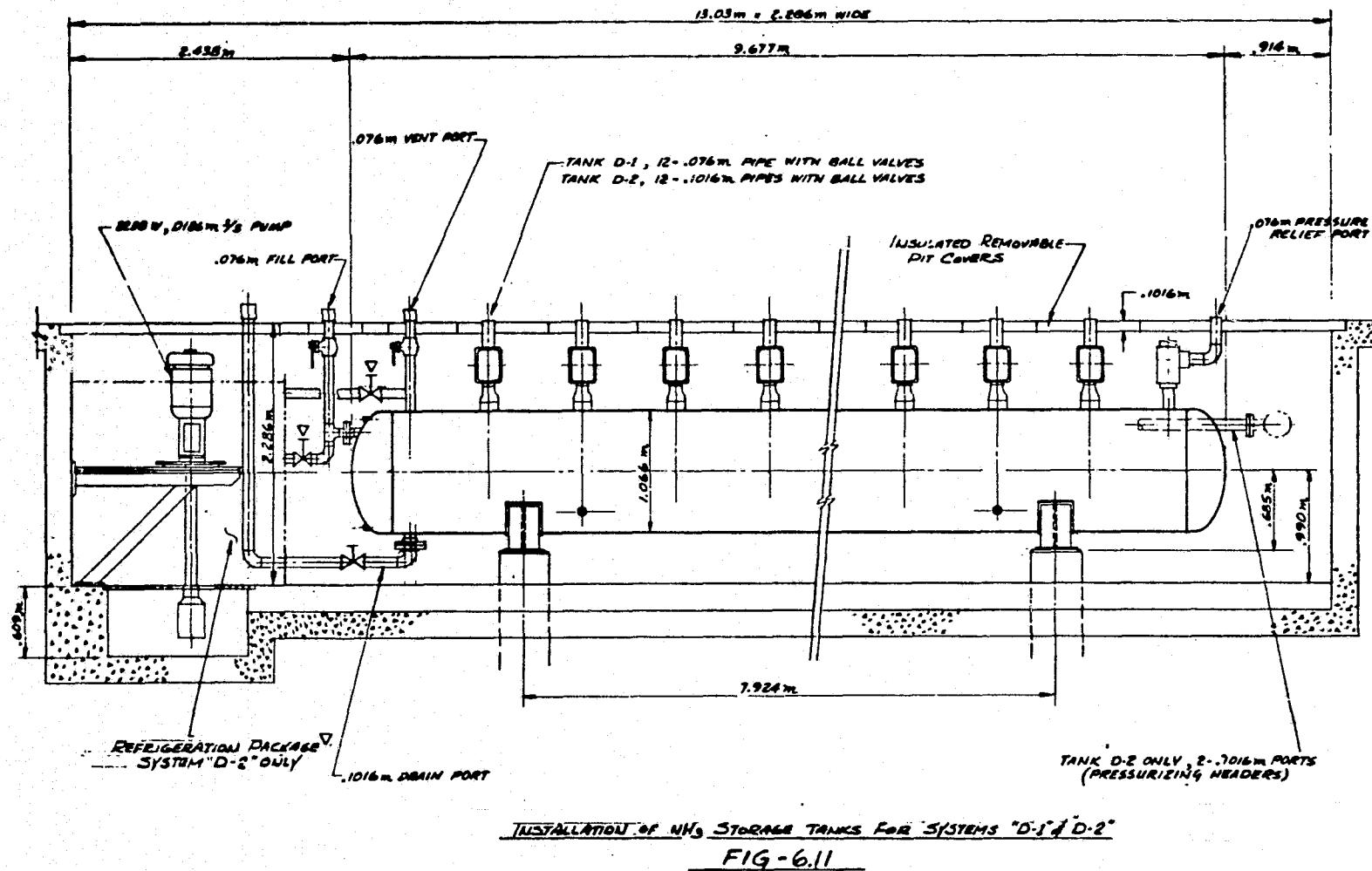
Gases or vapors which, in concentrations of the order of 1/2 to 1% for durations of exposure of the order of 1/2 hr, are lethal or produce serious injury.

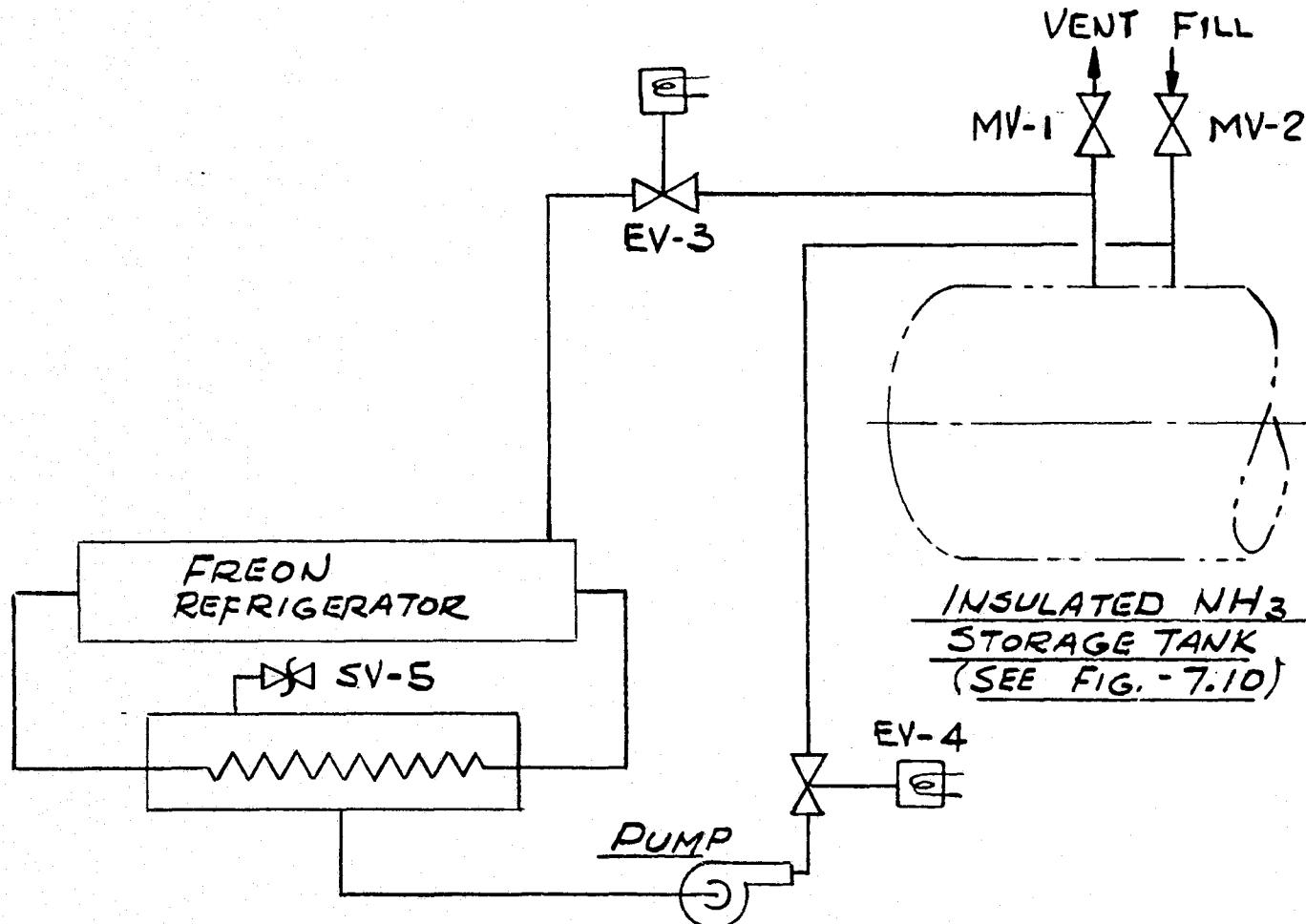
6.1.2.6 System D-2 - Neutralization by the Introduction of NH₃ Stored at -33°C.

System Description: This system requires two insulated 7.2 m³ tanks of the type shown in Figure 6.10, along with high pressure N₂ storage systems and refrigeration systems. The flow schematic of the system is incorporated in Figure 6.2. In addition, a refrigeration system is connected to each of the storage tanks as shown in Figure 6.12. The refrigeration system is a 1.4 x 10⁴ J/sec freon system which provides the necessary cooling to lower the temperature of the liquid NH₃ to -33°C and the pressure to atmospheric.

The storage tanks are constructed of Type 316 stainless steel and have a pressure rating of 1.72 x 10⁶ N/m². The outline of these tanks is shown in Figure 6.10. The tanks are equipped with twelve 0.1 m ball valves which serve as discharge nozzles. In addition to miscellaneous instrument taps, two 0.0762 m valve ports are provided to facilitate filling the tank. Since the temperature of the storage

¹ (of the same construction used for the high pressure storage pits)





INSTALLATION OF REFRIG. EQUIPMENT
FOR SYSTEM "D-2"
Typ. for 2-STORAGE TANKS

FIG. 6.12

tanks will be lowered to -33°C , it will be necessary to insulate the NH_3 storage tanks. 0.05 m of mineral fiber insulation plus a 1.27×10^{-2} m thick plaster coat and a weatherproof coating is required. As in the case of other systems, this work would be done in the field. The NH_3 tanks can be completely shop-fabricated and delivered to the site ready for installation.

Each tank is equipped with two 0.1 m N_2 supply pipe headers for connection to the high pressure N_2 supply systems. A 0.1 m drain connection is provided at the bottom of the tank for removing the NH_3 for maintenance purposes.

The discharge pressure for the system will be 2.55×10^5 N/m^2 absolute and will be obtained from the high pressure N_2 storage systems. Each high pressure storage system consists of a 137×10^5 N/m^2 storage tank having a water volume of 0.339 m³. The N_2 supply and dump valves are mounted in the same pit adjacent to the high pressure tanks as shown in Figure 6.5. The N_2 supply valves require a C_V of 10 and the dump valves require a C_V of 800. N_2 for the high pressure tanks will be provided by a N_2 compressor located in a protected area. The N_2 compressor requirements are 2.35×10^{-3} standard m³/sec @ 137×10^5 N/m^2 . Table XII shows the process points for System D-2.

System Operation: The NH_3 storage tanks will be filled in the same manner as for System D-1. When the tanks are at the required level, the refrigeration systems can be started and the process of cooling the liquid will begin. Approximately 24 hr of cooling will be required to bring the temperature of liquid to -33°C with a resulting tank pressure of atmospheric. The system can be held at this pressure and temperature continuously, thereby, reducing the safety hazards of storing NH_3 .

When the system is ready to be activated, the refrigeration systems are turned off and the pressure controller is set for 2.55×10^5 N/m^2 absolute. As with the carbonate systems, a signal will trigger the N_2 supply systems bringing the pressure up to 2.55×10^5 N/m^2 . At the same time, the twelve electrically-operated discharge valves will open and the ammonia will begin to discharge into the path of the exhaust gases. The system may be deactivated in the same way as the carbonate systems, however, no reclamation of the NH_3 will be possible. Should the system be deactivated for any reason, the refrigeration systems will need to be turned on again to restore and maintain the atmospheric pressure in the tanks.

TABLE XI

Process Points for System D-2
(Ammonia Neutralizing Agent)

<u>Point</u>	<u>Fluid</u>	<u>Pres. (Abs.)</u> <u>N/m²x10⁻⁵</u>	<u>Flow Rate*</u> <u>m³/sx10³</u>	<u>Line Size</u> <u>mx10²</u>
1	N ₂	137 (max)	2.359	2.67 OD x 1.88 ID
2	N ₂	137 (max)	1.179	2.67 OD x 1.88 ID
3	N ₂	137 (max)	1614	4.22 OD x 3.24 ID
4	N ₂	137 (max)	1614	4.22 OD x 3.24 ID
5	N ₂	137 (max)	1614	4.22 OD x 3.24 ID
6	N ₂	2.619	806 ¹	(2) 11.43 OD x 10.23 ID
7	N ₂	2.550	80.6 ²	(20) 11.43 OD x 10.23 ID
8	NH ₃	1.013	53.4 ³	(12) 11.43 OD x 10.23 ID
9	N ₂	137 (max)	1614	11.43 OD x 10.23 ID
10	N ₂	137 (max)	1614	11.43 OD x 10.23 ID
11	N ₂	137 (max)	1614	11.43 OD x 10.23 ID
12	N ₂	2.619	806 ¹	(2) 11.43 OD x 10.23 ID
13	N ₂	2.550	80.6 ²	(20) 11.43 OD x 10.23 ID
14	NH ₃	1.013	53.4 ³	(12) 11.43 OD x 10.23 ID

* At standard conditions.

¹ Flow for each of two 0.1 m lines.

² Flow for each of twenty 0.05 m lines.

³ Flow for each of twelve nozzles.

Installation: The installation of this system is identical to that of System D-1, except that refrigeration equipment and additional valving must be added in each pit. It will also be necessary to add the piping to the high pressure N₂ supply system. Figure 6.11 shows the installation requirements for the storage tanks and associated equipment. A 0.15 m pipeline will be required to connect to the high pressure N₂ supply system.

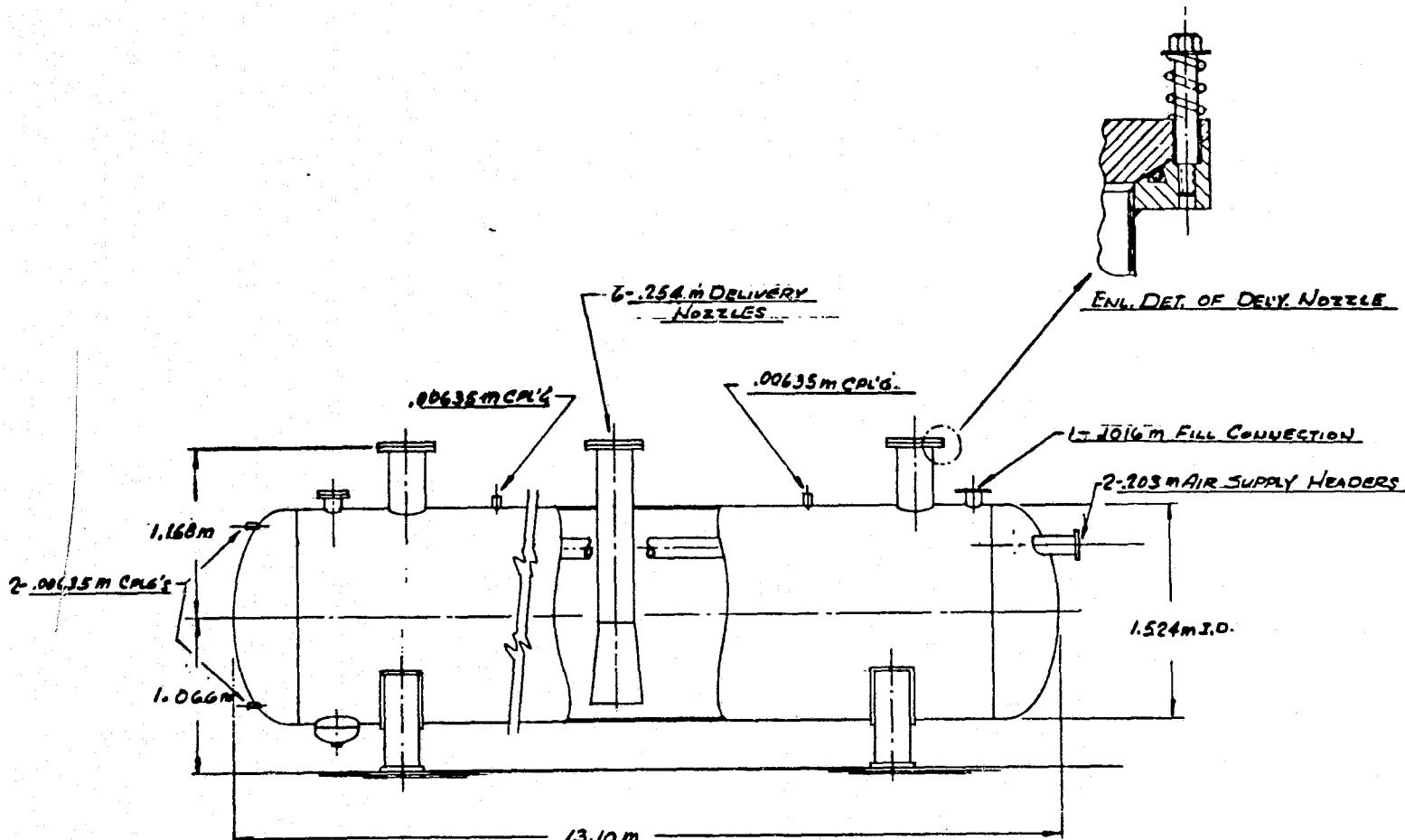
6.1.2.7 System E - Neutralization by the Introduction of NH₄OH. -

System Description: System E is similar to the carbonate systems. Figure 6.2 is again applicable as the schematic flow diagram of the system. The major components are the same as for System A and only differ in size. Figure 6.13 shows the neutralizer storage tank for System E. Further description of the system is identical to System A with the following exceptions:

- a) The neutralizer storage tanks have a capacity of 19.3 m³.
- b) Heating is not required.
- c) Two 0.1 m N₂ supply connections are provided.
- d) Six 0.25 m diameter discharge nozzles are provided with spring-loaded gasketed covers sealed with O-rings.
- e) The pressure to be maintained in the tanks is 1.72 x 10⁵ N/m² absolute.
- f) A water volume of 0.7 m³ is required for each of the high pressure storage systems.
- g) The N₂ supply valve requires a C_V of 20.
- h) The N₂ dump valve requires a C_V of 3200.
- i) Table XIII gives the process points for the system along with the required line sizes.

System Operation: The operation of System E will be identical to that of System A with the following exceptions:

- a) Each of the neutralizer storage tanks will be filled with 19.3 m³ of a 25% solution (by weight) of NH₄OH. A 0.1 m charging nozzle is provided for this purpose.
- b) The pressure controller will be set for 1.72 x 10⁵ N/m² absolute.
- c) The spring-loaded discharge nozzle covers will not open until the pressure in the tanks reach 1.24 x 10⁵ to 1.30 x 10⁵ N/m² absolute. A sealed system is required to prevent evaporation of the solution.



19.30 m³ NH₄OH DELIVERY TANK, FOR SYSTEM "E"
FIG. 6.13

T A B L E X I I I

Process Points for System E
(Ammonium Hydroxide Neutralizing Agent)

Point	Fluid	Pres. (Abs.) N/m ² x 10 ⁻⁵	Flow Rate* m ³ /s x 10 ³	Line Size m x 10 ²
1	Air	137 (max)	9.4	3.34 OD x 2.43 ID
2	Air	137 (max)	4.7	3.34 OD x 2.43 ID
3	Air	137 (max)	3227	6.03 OD x 4.92 ID
4	Air	137 (max)	3227	6.03 OD x 4.92 ID
5	Air	137 (max)	3227	6.03 OD x 4.92 ID
6	Air	1.79	1613 ¹	(2) 16.82 OD x 15.40 ID
7	Air	1.72	161.3 ²	(20) 11.43 OD x 10.23 ID
8	NH ₄ OH Sol.	1.013	320.8 ³	(6) 27.3 OD x 25.45 ID
9	Air	137 (max)	3227	27.3 OD x 25.45 ID
10	Air	137 (max)	3227	27.3 OD x 25.45 ID
11	Air	137 (max)	3227	27.3 OD x 25.45 ID
12	Air	1.79	1613 ¹	(2) 27.3 OD x 25.45 ID
13	Air	1.72	161.3 ²	(20) 27.3 OD x 25.45 ID
14	NH ₄ OH Sol.	1.013	320.8 ³	(6) 27.3 OD x 25.45 ID

* At standard conditions.

¹ Flow for each of two 0.152 m lines.

² Flow for each of twenty 0.1 m nozzles.

³ Flow for each of six nozzles.

d) Some of the solution will be lost due to evaporation during a reclamation process.

Installation: The installation of the delivery system is basically identical to System A. The differences are:

a) The high pressure tank and valving are piped to 0.25 m pipe which connects to the neutralizer tanks.

- b) Figure 6.7 is applicable except that the pit dimensions will be 17.98 m long by 2.74 m wide by 2.54 m deep and only two pedestals will be required.
- c) The support reactions will each be 11,340 kg.

6.2 ESTIMATED COST FOR DELIVERY SYSTEMS

System A, the sodium carbonate system, has been selected as the most suitable delivery system, however, since System D-1, the ammonia system, is relatively simple and small by comparison a cost estimate has been prepared for both systems. The estimated costs of these systems are as follows:

6.2.1 System A - Sodium Carbonate

- a) Two (2) shop-fabricated storage tanks, complete with pump, heaters and internal pipe headers @ \$43,000/each-----\$86,000.00
- b) One (1) lot of interconnecting piping materials, valves and fittings-----21,350.00
- c) One (1) lot of pressure, temperature and liquid level sensors with transmitters and local indicator devices; no remote control or readout devices are included-----5,900.00
- d) One (1) lot of steel grating pit covers and supports precut to size-----17,500.00
- e) Two (2) high pressure storage tanks @ \$4,200/each-----8,400.00
- f) Concrete work; two (2) concrete lined pits for neutralizing tanks with surrounding 12.2 m wide aprons and two (2) concrete lined pits for high pressure storage bottles; excavation costs are included @ \$32,300 per system-----64,600.00
- g) Field installation of two (2) neutralizer tanks including rigging, insulating and installation of pit covers and support structure-----16,450.00

- h) Field installation of two (2) high pressure gas storage bottles, pit covers and supports-----\$ 1,600.00
- i) Installation of all field piping, valves and controls-----9,000.00
- j) Power lines, disconnects and electrical equipment including installation-----17,200.00
- k) Total cost of equipment and installation \$ 248,000.00

6.2.2 System D-1 - Ammonia

- a) Two (2) shop-fabricated storage tanks, complete with drain, fill and discharge valves @ \$48,500/each-----\$ 97,000.00
- b) One (1) lot of fabricated, insulated pit covers and supports precut to size-----17,000.00
- c) One (1) lot of pressure, temperature and liquid level sensors with transmitters and local indicator devices; no remote control or readout devices are included-----4,500.00
- d) Concrete work; two (2) concrete lined pits for neutralizing tanks; excavation costs are included @ \$7,800/each-----15,600.00
- e) Field installation of two (2) neutralizer tanks, including rigging and installation of pit covers and support structure-----4,000.00
- f) Two (2) sump pumps, support brackets and installation-----4,300.00
- g) Power disconnects and electrical equipment, including installation-----7,200.00
- h) Total cost of equipment and installation---\$149,600.00

The preceeding estimates are based on prices effective March, 1976.

7. CONCEPTUAL DESIGN OF DELIVERY EQUIPMENT TO BE CARRIED BY AIRCRAFT

7.1 TYPES OF AIRCRAFT

Two helicopters and one airplane have been selected as the most suitable aircraft to be included in the conceptional design activity. The helicopters selected are the Boeing Chinook CH-47-C and the Sikorsky CH-54B. The airplane is a Lockheed C-130 E/H aircraft. These aircraft were selected on the basis of payload carrying capabilities, cargo space, ease of loading and endurance. All of the aircraft are standard types currently in use by the military and, consequently, more accessible.

The Chinook CH-47-C helicopter has an enclosed cargo space, 2.286 m wide by 1.98 m high by 9.3 m long. Loading is accomplished by way of a two-piece rear cargo door having an access opening 1.98 m high by 2.31 m wide. The door can remain open during flight and be locked in any position from fully open to fully closed. The CH-47-C has a total payload capacity (fuel plus cargo and crew) of 11.6×10^3 kg. The allowable floor loading in the cargo space is limited to 14.36×10^3 N/m² with a maximum capacity of 10.38×10^3 kg. A winch is provided in the cargo compartment to facilitate the loading of cargo. With single reeving the winch is limited to a 1,360 kg pulling load, however, by doubling or tripling the reeving the capacity will increase by a factor of 2 or 3.

The Sikorsky CH-54B helicopter does not have an enclosed cargo compartment. Instead, the cargo is carried externally on the underside of the fuselage directly below the rotor. A four-point suspension system is provided on the sides of the fuselage to support the cargo. Each of the suspension points has a 3,765 kg capacity and is equipped with 3.66 m of adjustable cable and a damping device to isolate aircraft or load vibration. Loads may be carried suspended or snubbed directly against the fuselage. In order to provide maximum lift capability the width of the cargo is limited to 2.13 m. The depth of the cargo is limited by the ground clearance which is 2.84 m and the length can be as much as 9.14 m. The total payload that can be carried is 12.36×10^3 kg.

The Lockheed C-130 E/H airplane has a useable cargo space 2.74 m wide by 2.74 m high by 12.32 m long. The floor of the cargo compartment is equipped with a series of roller assemblies which make it easy to load heavy cargo aboard the

aircraft. A two-piece cargo door having a 3.05 m wide by 2.77 m high access opening is provided at the rear of the aircraft. Like the cargo door of the Chinook, this door may remain open during flight: The lower half of the door can be locked in any position while the upper half of the door is stored in the tail section of the aircraft if desired. The allowable floor loading in the cargo compartment varies with location. The section directly below the wing can handle cargo loads as high as 15.8×10^3 kg while the allowable load in the forward and aft sections rapidly diminishes to 1,360 kg at the two extremes. Heavy-duty sectional pallets approximately 2.74 m wide and 2.24 m long having an allowable floor loading of 3.45×10^5 N/m² are available and can be securely latched to the aircraft by means of locking rails which span the entire length of the cargo space on both sides of the floor. The maximum allowable cargo load is limited to 20.4×10^3 kg.

7.2 DELIVERY TECHNIQUE

Neutralization of the HCl in the exhaust gases above ground is best carried out in the column cloud where the velocities are still relatively high and mixing of the neutralizing agent and the HCl readily occurs. Since the column cloud reaches the inversion layer within 12 min after launch and the last large portion of the tunnel cloud enters the inversion layer within another 12-15 min, it becomes necessary to deliver all of the neutralizing agent between times $T + 4$ and approximately $T + 27$ min. In order to accomplish this and provide some additional time for variation in cloud rates of rise, it will be necessary to fly all of the required aircraft simultaneously.

A total of three helicopters, each carrying 5,443 kg of NH₃ can complete the delivery in 9 min. If two airplanes, each carrying 8,165 kg of NH₃ are used, approximately 12 min will be required to complete the delivery. The helicopters can simultaneously fly at altitudes approximately 300 m apart with the uppermost helicopter flying at the highest altitude where the cloud density is still high. In this manner, maximum residence time in the cloud is afforded to the aircraft and the effective coverage and neutralization activity is enhanced. In the case of the two airplanes, the spacing can be increased to 450 m with the uppermost aircraft again selecting an elevation just below the point where the cloud begins to disperse. Regardless of the type of aircraft used, the procedure will be to fly at a fixed elevation, continually making Figure 8 flight patterns with

the cross being made within the column cloud. Under some conditions, it is conceivable that the cloud may enter the inversion layer or become widely dispersed before all of the neutralization agent has been delivered. Under these conditions, the final delivery passes can be made by flying above the cloud formation at the inversion layer and spraying the balance of the NH₃ into the final cloud. For a summary of aircraft flight and delivery data refer to Table XIV.

T A B L E X I V
Summary of Aircraft Flight and Delivery Data

	Boeing Chinook <u>CH-47-C</u>	Sikorsky <u>CH-54B</u>	Lockheed <u>C-130 E/H</u>
1. Aircraft:			
2. Type of Aircraft:	Helicopter	Helicopter	Airplane
3. No. Required:	Three (3)	Three (3)	Two (2)
4. Total No. Passes Each Aircraft:	Eleven (11)	Eleven (11)	Six (6)
5. Average Flight Speed:	18 m/s	18 m/s	64.3 m/s
6. Average Time in Column Cloud:	13.6 sec	13.6 sec	3.8 sec
7. Average Time to Make a Figure 8:	1.5 min	1.5 min	4 min
8. Total Flight Time for Delivery/ Aircraft:	9 min	9 min	12 min
9. Allowable Flying Time per Aircraft Based on Fuel Carried:	1.4 hr	1.4 hr	1.4 hr
10. Capacity of Fuel Tanks:	3,332 kg	4,082 kg	27.2×10^3 kg
11. Max. Takeoff Wt.:	20.86×10^3 kg	21.32×10^3 kg	70.31×10^3 kg
12. Max. Landing Wt.:	20.86×10^3 kg	21.32×10^3 kg	58.97×10^3 kg
13. Wt. of Empty Aircraft:	9,253 kg	8,960 kg	33.11×10^3 kg
14. Wt. of NH ₃ to be Carried/Aircraft:	5,443 kg	5,443 kg	8,165 kg

TABLE XIV (Continued)

	<u>Boeing Chinook CH-47-C</u>	<u>Sikorsky CH-54B</u>	<u>Lockheed C-130 E/H</u>
15. Wt. of NH ₃ Tank w/Skid or Support Frame:	3,810 kg	3,039 kg	3,493 kg
16. Wt. of Delivery Module:	272 kg	-	1,450 kg
17. Amount of Fuel to be Carried:	1,588 kg	2,495 kg	3,946 kg
18. Total Takeoff Wt.:	20.37×10^3 kg	19.938×10^3 kg	50.17×10^3 kg
19. Reserve Payload Capacity for Crew & Misc. Equip.:	499 kg	1,381 kg	20.14×10^3 kg
20. Volume of NH ₃ / Aircraft:	8.97 m^3	8.97 m^3	13.45 m^3
21. Delivery Rate of NH ₃ per System:	$6 \times 10^{-2} \text{ m}^3/\text{s}$	$6 \times 10^{-2} \text{ m}^3/\text{s}$	$59 \times 10^{-2} \text{ m}^3/\text{s}$
22. Cost of NH ₃ :	\$4,500	\$4,500	\$4,500
23. System Cost:	-	\$114,450	-

7.3 DESIGN CRITERIA

The criteria for designing aircraft delivery systems are in accordance with the following:

- a) Each of the systems have been sized on the basis of neutralizing only the column cloud which has been estimated to contain 34×10^3 kg of HCl.
- b) The neutralizing agent to be used is NH₃ stored at ambient temperature. A 10% excess amount is provided.
- c) The flow rates of the NH₃ were determined on the basis of the following:
 - 1) A nominal cloud diameter of 244 m.
 - 2) Helicopter air speeds of 18 m/sec.

- 3) Three helicopters to be used, each making eleven passes within 9 min based on completing a Figure 8 in 1.5 min.
- 4) Air speeds of 64.3 m/sec for the C-130 E/H aircraft.
- 5) Two airplanes to be used, each making six passes within 12 min based on completing a Figure 8 within 4 min.
- d) The systems must meet center of gravity and floor loading requirements for their respective aircraft.
- e) A fuel supply providing at least 1.4 hr of flying time can be loaded aboard the aircraft and together with the delivery systems and crew not exceed maximum takeoff weights.
- f) The installation of delivery systems can be accomplished with a minimum of alterations to the aircraft.
- g) The delivery systems can be easily and quickly installed and removed from aircraft.
- h) All storage tanks were designed in accordance with Section VIII, Division 1 of the ASME Code.
- i) Storage tanks are constructed of SB-209-5456 H-321 aluminum.
- j) The system design parameters are as follows:

<u>System</u>	<u>Design Pressure</u>	<u>Design Temp.</u>
Chinook CH-47-C	$13.79 \times 10^5 \text{ N/m}^2$	43°C
Sikorsky CH-54B	$17.24 \times 10^5 \text{ N/m}^2$	46°C
Lockheed C-130 E/H	$13.79 \times 10^5 \text{ N/m}^2$	43°C

- k) A failure of any one discharge valve to open or close will not adversely affect control of the aircraft.

7.4 NH₃ DELIVERY SYSTEM FOR THE CHINOOK CH-47-C HELICOPTER

7.4.1 System Description

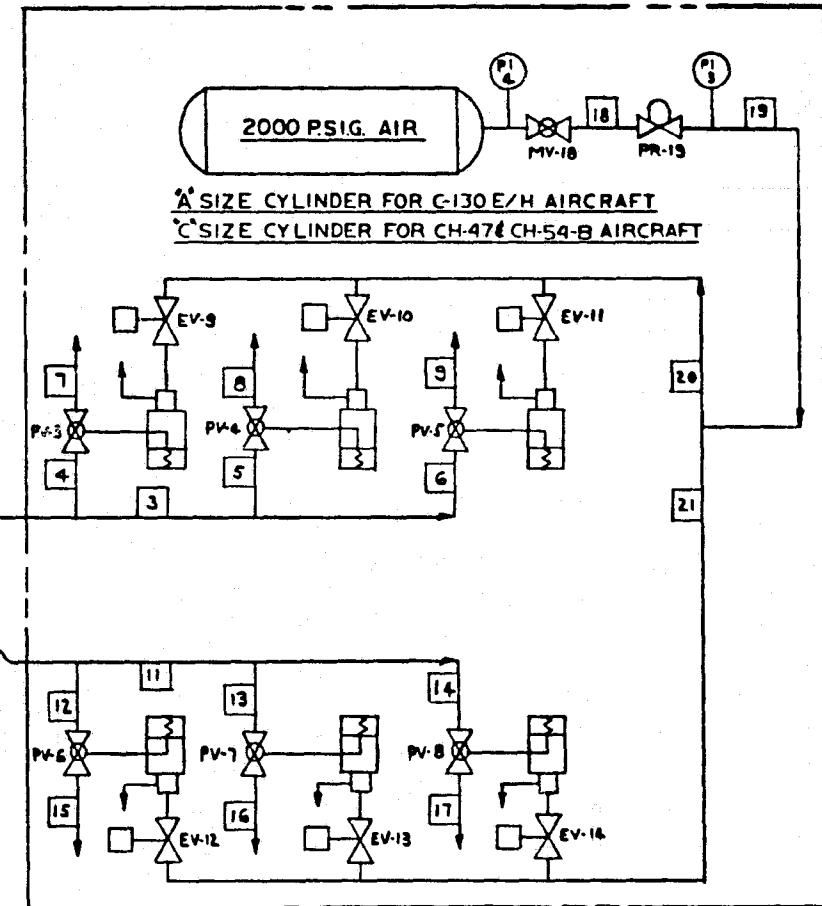
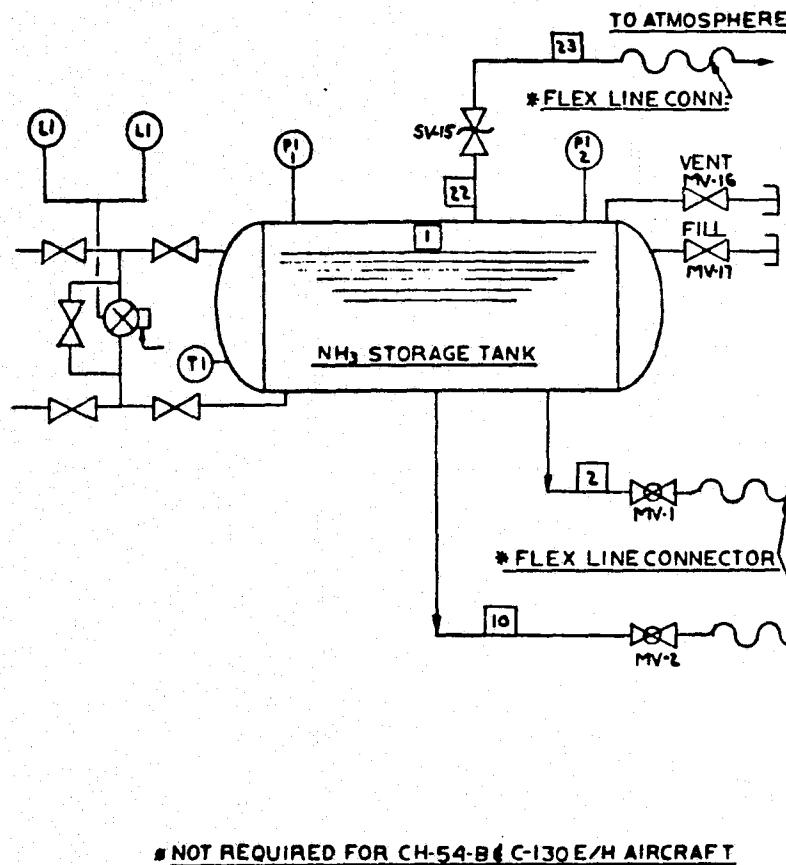
The system is shown schematically in Figure 7.1. Each of three helicopters will be equipped with a skid-mounted storage tank and a delivery module as shown in Figure 7.2. The delivery module consists of six pneumatically actuated 0.038 m³ ball valves having a nominal Cv rating of 90, a 137 x 10⁵ N/m² "C" size air storage bottle and various pressure indicators and regulating devices. The module is an integrated delivery system mounted on a skid for convenience and to provide easy installation and removal from the helicopter. The delivery module is coupled to the storage tank via three flexible corrugated line connectors and are the only piping connections required between the two components.

The storage tank has a capacity of 8.97 m³ and is constructed of aluminum for a design pressure of 13.79 x 10⁵ N/m². The tank is provided with two 0.1 m manually operated isolation ball valves to permit filling the tank with or without the delivery module in place. If necessary, a hose could be connected to one of the valves and the tank can be drained into another storage container. These valves also serve to provide a positive means of stopping the flow of NH₃ in the event the discharge valves fail to close or leak. A 0.05 m fill and 0.076 m vent valve are provided at the top of the tank to enable filling the storage tank from a standard NH₃ delivery vehicle. For convenience of operation, pressure and liquid level gauges are provided at two locations. One location is the end of the tank where the filling connections are made and another is the opposite end of the tank where a panel plate is mounted on the tank to serve as a control station.

The process points along with the required line sizes are given in Table XV.

7.4.2 System Operation

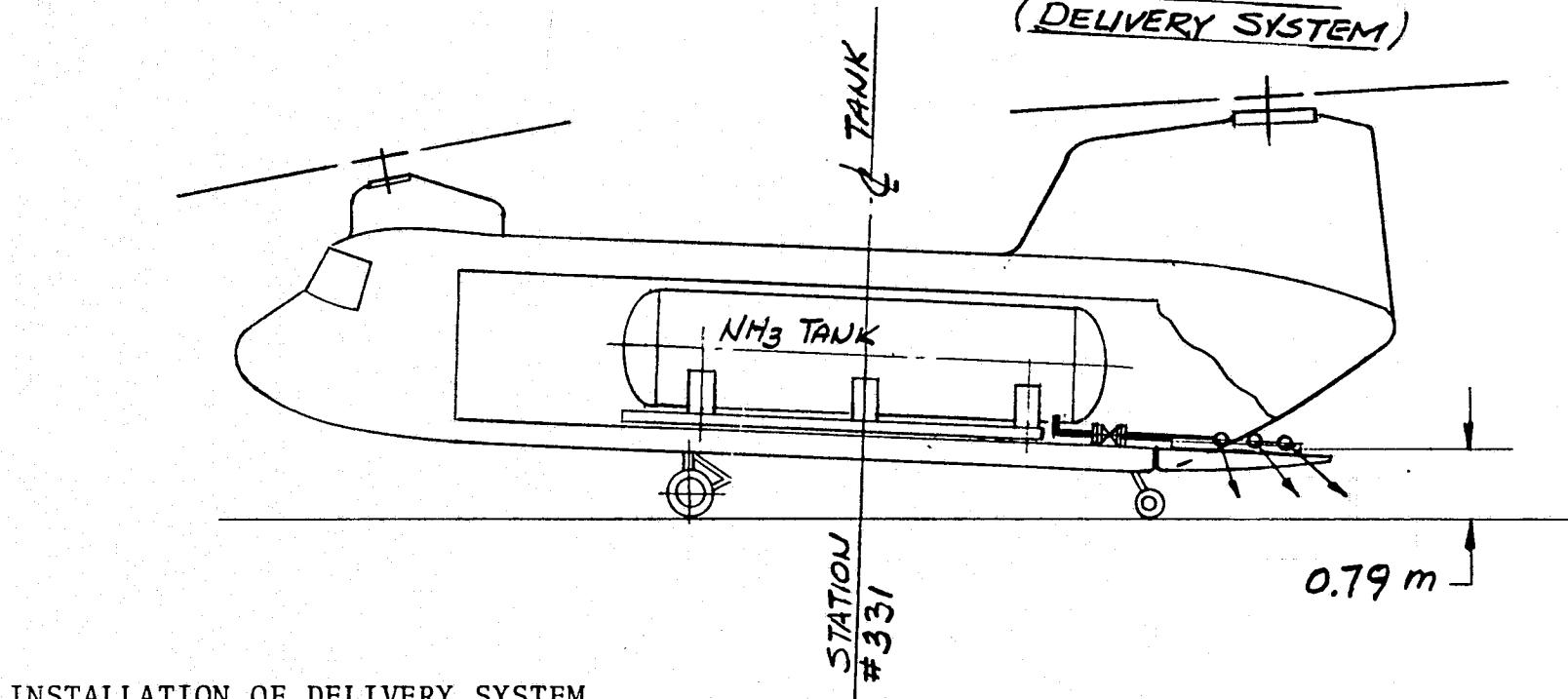
Initially, 8.97 m³ of NH₃ are pumped into the storage tank in accordance with the scheme presented in Section 6.1.2.5 under "System Operation". The filling operations are carried out with the tank anchored in the proper position within the aircraft and all valves closed. A routine check is made to verify that all connections within the delivery module and interconnecting piping are intact and that the delivery module is secured to the aircraft. The high pressure shutoff valve is opened and the pressure regulator PR-13 is adjusted to



NH₃ DELIVERY SYSTEM FOR CH-47C (CH-54B & C-130 E/H AIRCRAFT

FIG-7.1

HELICOPTER MAX. TAKE-OFF WEIGHT:	20,860 kg
HELICOPTER WEIGHT (EMPTY):	9,253 kg
WEIGHT OF NH ₃ TANK (EMPTY) & DEL. MOD.:	4,082 kg
WEIGHT OF NH ₃ SOLUTION:	5,443 kg
MAXIMUM FUEL TO BE LOADED:	1,588 kg
TOTAL FLYING TIME:	1.4 hr



INSTALLATION OF DELIVERY SYSTEM
IN CH-47-C HELICOPTER

FIGURE 7.2

T A B L E X V

Process Points for the NH₃ Delivery Systems for the
Chinook CH-47-C and Sikorsky CH-54B Helicopters
(See Figure 7.1)

Point	Fluid	Pres. N/m ² x 10 ⁻⁵	(Abs.)	Flow Rate	Temp.	Line Size m x 10 ²
1	NH ₃	8.82		18.28 kg/s	21°C	
2	NH ₃	8.82		18.28 kg/s	21°C	11.43 OD x 10.23 ID
3	NH ₃	8.79		18.28 kg/s	21°C	11.43 OD x 10.23 ID
4, 5 & 6	NH ₃	8.77		6.1 kg/s	21°C	8.89 OD x 7.79 ID
7, 8 & 9	NH ₃	1.013		6.1 kg/s	-33°C	8.89 OD x 7.79 ID
10	NH ₃	8.82		18.28 kg/s	21°C	8.89 OD x 7.79 ID
11	NH ₃	8.79		18.28 kg/s	21°C	8.89 OD x 7.79 ID
12, 13 & 14	NH ₃	8.77		6.1 kg/s	21°C	8.89 OD x 7.79 ID
15, 16 & 17	NH ₃	1.013		6.1 kg/s	-33°C	None
18	Air	137 (max)		17.93 x 10 ⁵ m ³ /s*	21°C	2.13 OD x 1.58 ID
19	Air	7.93		17.93 x 10 ⁵ m ³ /s*	21°C	2.13 OD x 1.58 ID
20	Air	7.93		8.96 x 10 ⁵ m ³ /s*	21°C	2.13 OD x 1.58 ID
21	Air	7.93		8.96 x 10 ⁵ m ³ /s*	21°C	2.13 OD x 1.58 ID
22	NH ₃	14.82		.24 kg/s	46°C	3.34 OD x 2.66 ID
23	NH ₃	1.013		.24 kg/s	-1°C	6.0 OD x 5.48 ID

*At standard conditions.

provide a pressure reading of 6.9×10^5 N/m² on gauge PI-3. The operation of all the discharge valves can then be checked by depressing an activation button which will allow the air pressure to operate the valve actuators opening all the valves simultaneously. Depressing a second button will allow the valves to return to their closed positions, thus verifying

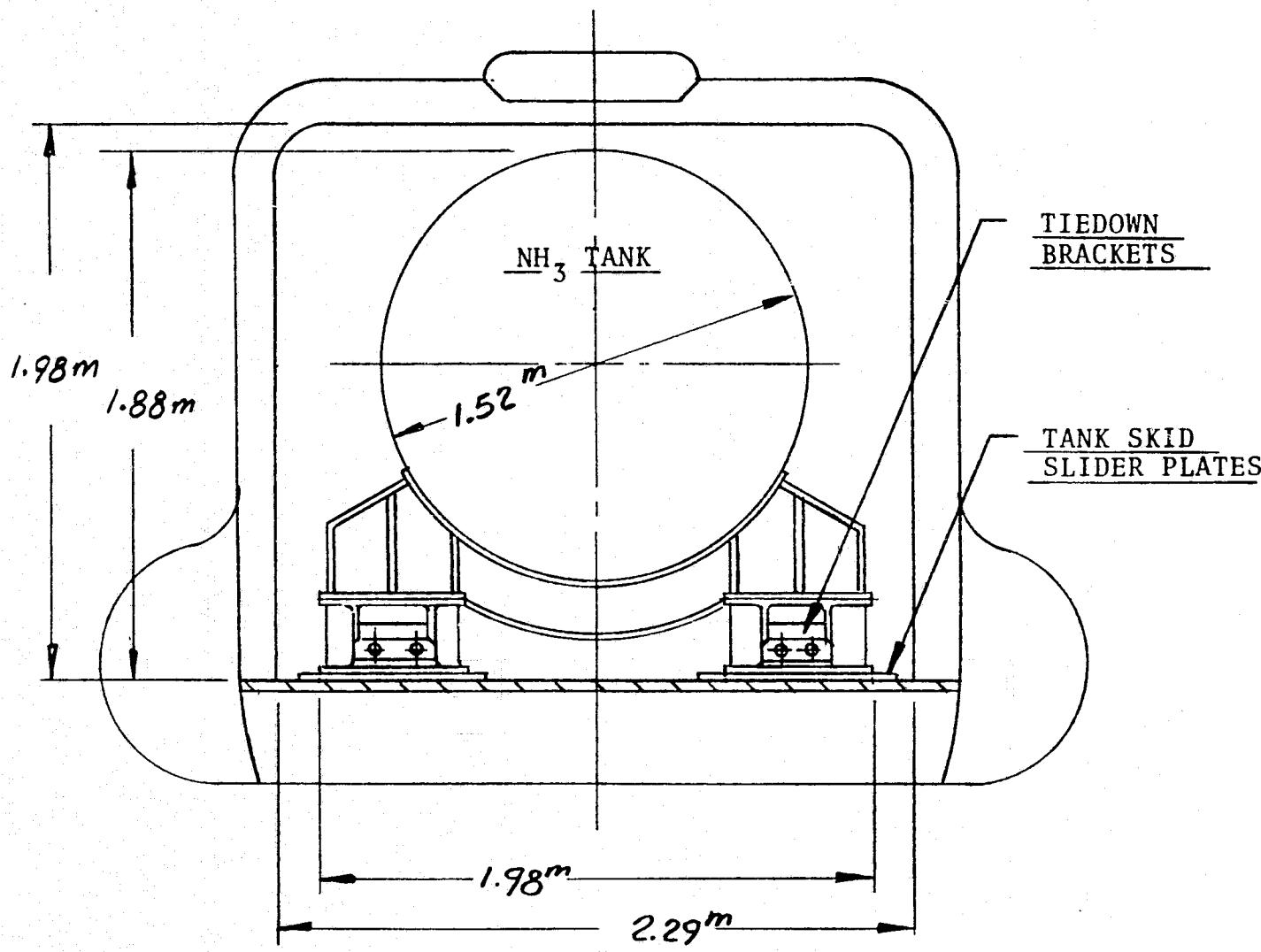
proper operation of the delivery system. The main shutoff valves, MV-1 and MV-2, can then be opened, thus rendering the system ready for operation.

With the aircraft in flight at the required elevations, the system is activated and deactivated just as the aircraft enters and leaves the column cloud. The NH₃ will be discharged at the rear of the helicopter through discharge valves PV-3 through PV-8. The three valves on each side of the aircraft will be positioned for different projectile paths, thereby, providing more effective coverage. The reach of the NH₃ streams will be quite large since the material leaves the valves at sonic velocity.

7.4.3 Installation

In order to install the NH₃ storage tank in the aircraft, it will be necessary to provide a suitable sliding surface over the existing cargo floor. This can be provided by securing two 0.0047 m thick by approximately 7 m long abrasion resistance plates to the floor at the bearing points of the tank skid. With the aid of a standard mobile cargo loader and the winch provided in the cargo compartment, the storage tank can be pulled from the loader and slid across the skid plates into the required position in the aircraft. The installation must be done with the tank empty since a filled tank can create excessively high concentrated loads on the flooring in addition to making the installation work more difficult. Once the tank is in position, the tank can be secured to the cargo floor by bolting angle brackets to the skid and floor as shown in Figure 7.3.

The delivery system, pipes and valves are mounted on a common support base which must be anchored to the cargo door platform at the rear of the aircraft. To do this the cargo door operators are actuated to move the door into a position parallel to the cargo floor. The delivery module can then be installed, aligned and connected to the storage tank piping by way of the flexible line connectors. Once in position, the delivery module can be anchored to the tiedown fittings provided on the cargo door. With initial modifications completed on the aircraft, the total installation time for the complete system should be 2-3 hrs at the most. An electric power source will be required to operate the solenoid valves on the valve actuators. The six valves will require a total of 90 W for approximately 15 sec intervals. This power may be taken from the aircraft's 28 VDC power supply or a 12 VDC 90 amp hr battery could be mounted on the tank skid and the appropriate coils be installed in the solenoid valves.



INSTALLATION OF NH_3 TANK IN CHINOOK CH-47C

FIGURE 7.3

7.5 NH₃ DELIVERY SYSTEM FOR THE SIKORSKY CH-54B HELICOPTER

7.5.1 System Description

The delivery system for each of the three CH-54B helicopters is similar to that of the Chinook CH-47-C, the main difference being that the discharge valve assemblies are mounted on the sides of the storage tank integrating the entire system into a single package. The schematic of the system and the process points and line sizes are again as shown in Figure 7.1 and Table XV.

This system is the simplest and most convenient of the three systems presented in this report. No modifications are required of the aircraft, except to install instrument and control lines between the flight cabin and storage tank components. The storage tank is provided with square-shaped support structures at the ends of the tank which serve as mounting attachment points for the four-point suspension system and support saddles when the tank is resting on the ground. Since the storage tank is carried externally on this aircraft, the pressure rating has been increased to 17.24 x 10⁵ N/m² to prevent the safety valve from discharging in the event of a temperature increase resulting from prolonged exposure to direct sunlight. The temperature corresponding to this pressure is 46°C.

7.5.2 System Operation

The operation and checkout of the system is identical to that of the Chinook CH-47-C except that the tank may be filled, if desired, before attaching it to the underside of the aircraft. In this case, the helicopter is simply positioned over the tank and the four hydraulically operated suspension cables will lift and snug the assembly to the underside of the aircraft. Activation and deactivation of the system will be from within the flight cabin where a control panel is conveniently mounted to monitor the pressure, temperature and contents of the NH₃ storage tank. As with the case of the CH-47-C the valves are positioned to produce different projectile paths.

7.5.3 Installation

The tank and delivery system is mounted to the underside of the helicopter as a complete unit as shown in Figure 7.4. Two lifting lugs are provided on each of the two support structures of the tank in line with the existing four-point suspension system on the helicopter. With the storage tank resting on the ground a clearance of approximately 0.5 m will exist between the underside of the fuselage and the tank supports. The tank can be lifted against the helicopter fuselage by attaching the extendable 3.66 m cables and activating the lift mechanism. This completes the installation of the delivery system, except for instrumentation connections.

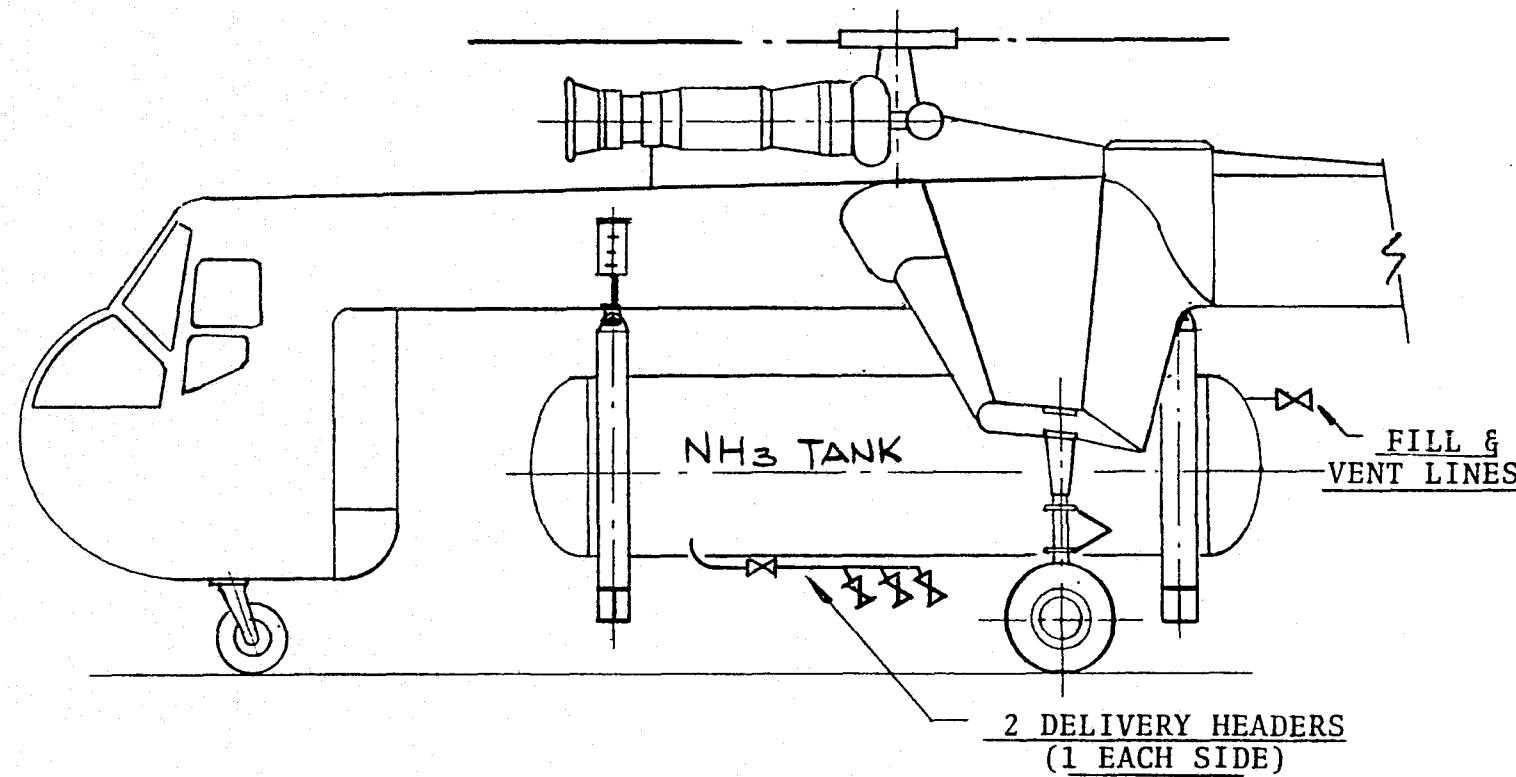
It will be necessary to install an instrument line manifold and electrical terminal block on the fuselage close to the tank. Two 0.0064 m lines, a pair of thermocouple leads and a power cable will have to be routed from the control panel in the flight cabin to these junction points. The installation work is completed by attaching lines and leads from the storage tank to the junction blocks. The electrical requirements for this system are the same as for the Chinook CH-47-C. Once the control panel, instrumentation and power leads are installed on the helicopters, the time required to install or remove the delivery system will be less than 1 hr.

7.6 NH₃ DELIVERY SYSTEM FOR THE LOCKHEED C-130 E/H AIRPLANE

7.6.1 System Description

Each of two C-130 E/H airplanes will be equipped with a 13.45 m³ storage tank and a detachable delivery module of a similar arrangement to the Chinook CH-47-C. The delivery module utilizes six pneumatically actuated 0.1 m ball valves with a nominal C_v rating of 775. The valve assemblies are mounted on a common support base provided with adjustment features to facilitate installation and alignment of the pipe headers with the supply lines on the storage tank. Figure 7.1 is again applicable as the flow sheet of the system. As with the previous systems, three valves discharge NH₃ on each side of the aircraft. A 0.91 m wide existing doorway on each side of the airplane provides the necessary opening to accommodate the valves and their operators. A segment of a pipe elbow is attached to the discharge end of each valve. Three different arc segments are used and each of the elbows are turned several degrees off the vertical plane to provide varying projectile paths in a direction down and away from the plane.

HELICOPTER MAX. TAKE-OFF WEIGHT: 21,320 kg
HELICOPTER WEIGHT (NO CARGO): 8,960 kg
WEIGHT OF NH₃ TANK (EMPTY)
WITH DELIVERY SYSTEM: 3,039 kg
WEIGHT OF NH₃ SOLUTION: 5,443 kg
MAX. FUEL TO BE LOADED: 2,495 kg
TOTAL FLYING TIME: 1.4 hr



Attachment of the NH₃ Delivery System to a Sikorsky CH-54B Helicopter

FIGURE 7.4

The storage tank is supported by four support saddles which are mounted on two wide flange beams to provide safe floor loading conditions and to facilitate installation. The skid-mounted tank will be bolted to a four-section standard aluminum cargo pallet having a $3.4 \times 10^5 \text{ N/m}^2$ rating. The storage tank is also provided with a control panel which is mounted on the end head closest to the flight cabin. The delivery module will also be bolted to a pallet, however, it will be necessary to reduce the length of the standard pallet for this purpose. Two 0.3 m ball valves are provided between the storage tank and delivery module for isolation purposes. These valves are provided with a gear box and handwheel for manual operation. The process points and line sizes are shown in Table XVI.

7.6.2 System Operation

Initially, 13.45 m^3 of NH_3 are pumped into the storage tank and a check is made of all connections in the same manner as for the Chinook CH-47-C. The operation is also identical, except that the NH_3 will be discharged through the side doors of the aircraft and the main cargo door at the rear of the aircraft can be closed during flight.

7.6.3 Installation

As indicated previously, both the tank and the delivery module are mounted to cargo pallets. By loading the tank/pallet system onto a standard cargo loader, the entire assembly can easily be moved to the inside of the aircraft by pushing or pulling the tank across the roller supports on the cargo floor. The delivery system is loaded aboard the aircraft in the same way, however, it will be necessary to swing the discharge valve assemblies into a vertical position to clear the sides of the aircraft. Once the module is properly positioned, the valve assemblies can be lowered and swung through the doorways on both sides of the plane.

Both the tank and delivery module can then be secured to the aircraft by means of the existing pallet latching mechanisms located on both sides of the aircraft floor. The installation is completed by bolting together two 0.3 m and one 0.05 m pipe connections between the storage tank and delivery module, and connecting electrical power to the equipment. The electrical requirements are the same as for the CH-47-C. The installation of the delivery systems in the C-130 E/H aircraft is shown in Figure 7.5.

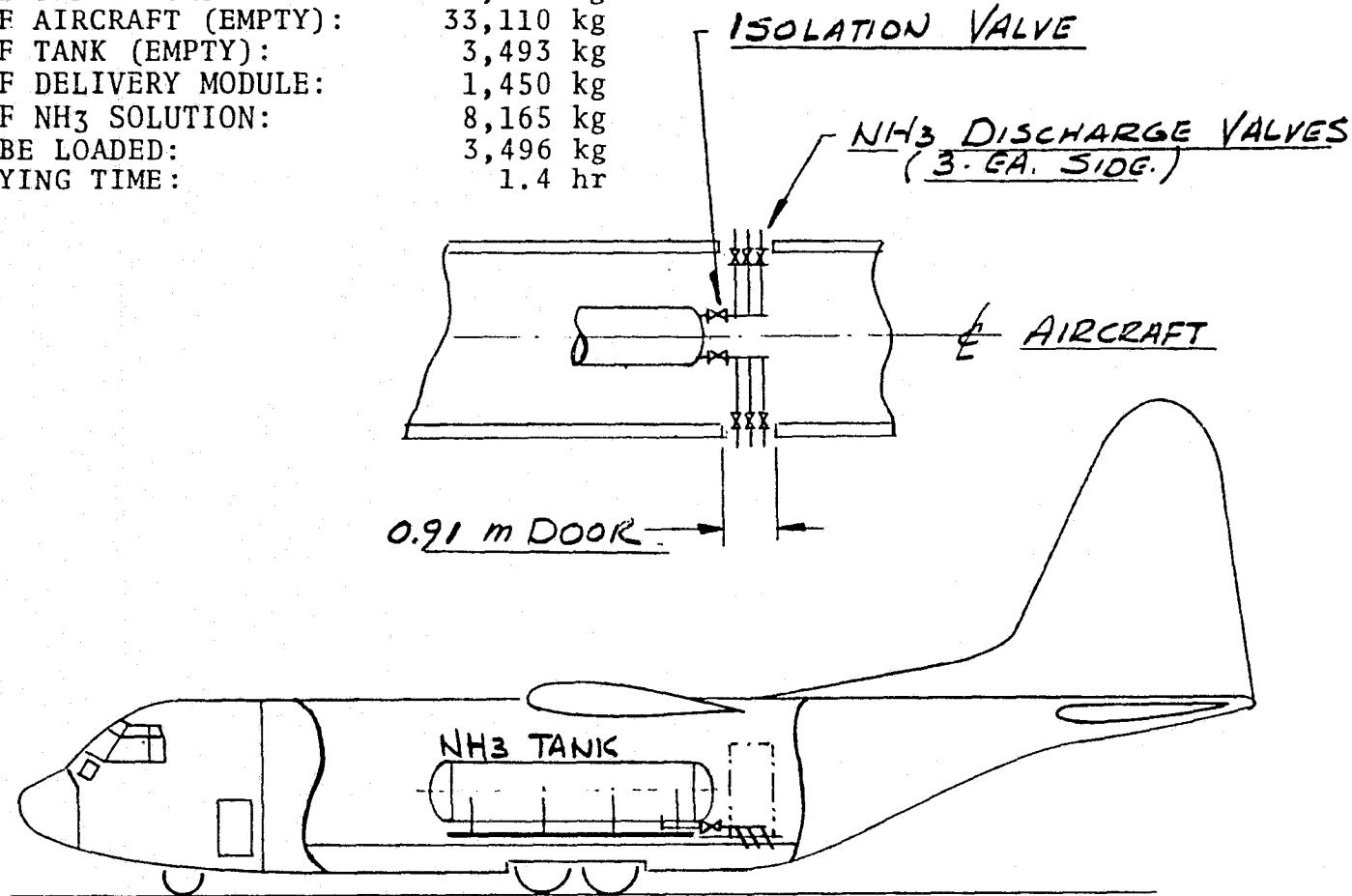
TABLE XVI

Process Points for the NH₃ Delivery
System for the C-130 E/H Airplane
(See Figure 7.1)

<u>Point</u>	<u>Fluid</u>	<u>(Abs.) Pres. N/m²x10⁻⁵</u>	<u>Flow Rate</u>	<u>Temp.</u>	<u>Line Size m x 10²</u>
1	NH ₃	8.82		21°C	
2	NH ₃	8.82	180 kg/s	21°C	32.38 OD x 30.48 ID
3	NH ₃	8.75	180 kg/s	21°C	32.38 OD x 30.48 ID
4, 5 & 6	NH ₃	8.72	59.87 kg/s	21°C	21.90 OD x 20.27 ID
7, 8 & 9	NH ₃	1.013	59.87 kg/s	-33°C	11.43 OD x 10.82 ID
10	NH ₃	8.82	180 kg/s	21°C	32.38 OD x 30.48 ID
11	NH ₃	8.75	180 kg/s	21°C	32.38 OD x 30.48 ID
12, 13 & 14	NH ₃	8.72	59.87 kg/s	21°C	32.38 OD x 30.48 ID
15, 16 & 17	NH ₃	1.013	59.87 kg/s	-33°C	32.38 OD x 30.48 ID
18	Air	137 (max)	0.11m ³ /s*	21°C	2.13 OD x 1.57 ID
19	Air	7.93	0.11m ³ /s*	21°C	3.34 OD x 2.66 ID
20	Air	7.93	0.055m ³ /s*	21°C	2.66 OD x 2.1 ID
21	Air	7.93	0.055m ³ /s*	21°C	2.66 OD x 2.1 ID
22	NH ₃	14.82	0.2 kg/s	46°C	4.83 OD x 4.09 ID
23	NH ₃	1.013	0.2 kg/s	-1°C	6.03 OD x 5.25 ID

*At standard conditions.

MAX. TAKE-OFF WEIGHT:	70,310 kg
WEIGHT OF AIRCRAFT (EMPTY):	33,110 kg
WEIGHT OF TANK (EMPTY):	3,493 kg
WEIGHT OF DELIVERY MODULE:	1,450 kg
WEIGHT OF NH ₃ SOLUTION:	8,165 kg
FUEL TO BE LOADED:	3,496 kg
TOTAL FLYING TIME:	1.4 hr



Installation of Delivery System in C-130 E/H Aircraft

FIGURE 7.5

7.7 ESTIMATED COST FOR DELIVERY SYSTEMS

The Sikorsky CH-54B helicopter and associated delivery system has been selected as the most suitable means of delivering NH₃ into the column cloud. A cost estimate has been prepared for this system and is as follows:

- a) Fabricated tank with delivery system, instrumentation, controls, valves and all components required for operation-----\$ 36,650.00/each
- b) Modification to CH-54B helicopter; Installation of control panel, instrument and control lines and battery pack-----1,500.00/each
- c) Cost per system-----38,150.00/each
- d) Total cost for three systems-----\$114,450.00/total

The preceding cost estimate does not include the acquisition of three Sikorsky CH-54B helicopters and is based on prices effective March, 1976.

8. SAMPLING TECHNIQUES

The success of the neutralization of the HCl generated in the ground cloud and column cloud of the space shuttle launch can only be determined by proper sampling of the cloud. The state-of-the-art in measuring instruments for air quality during the late sixties is summarized in Table XVII (ref. 10). Generally, these measurements were concerned with CO₂, CO, NO₂, NO, oxidants, SO₂, O₃, total hydrocarbons and general particulates and aerosols. Generally, these instruments were unsatisfactory since they were based on engineering designs that were ten to fifteen years old. The instruments were insensitive, had slow data rates and were difficult to standardize and calibrate.

Proper sampling techniques require a method of moving the sample through the measuring instrument, measuring the quantity of sample and collecting or analyzing the sample. Air movers for stationary instrumentation are generally compressors and vacuum pumps. In the case of aircraft sampling, a properly designed probe will permit direct movement of the sample through the instrument and measurement of the quantity of sample. Rotometers, orifices and gas meters permit the measurement of the quantity of sample passed through the analytical instrument or collecting device. Collectors include centrifugal, impaction, electrostatic or thermal precipitators for particulate pollutants while gaseous materials are collected by adsorption in liquid, adsorbed on solids or condensed in cold traps.

Many of the current developments in the analysis of inorganic pollutants are directed toward the increasing use of automated instrumentation. Frequently, this automated instrumentation is associated with digital computers so that the evaluation of the data can be readily accomplished by suitable computer programs.

8.1 SAMPLING NEEDS

Calculations of the expected HCl concentration in the ground cloud and column cloud as a function of time indicates that as the cloud size increases with time the HCl concentration reaches low levels (less than 10 ppm) in a relatively short time. These low HCl concentrations are difficult to sample. In addition, the interaction between the HCl gas and particulates (Al₂O₃) is an important phenomenon not completely understood. Instruments are needed which will

T A B L E X V I I
Measurement Principles in Air Quality Monitoring

<u>Classification</u>	<u>Application</u>	<u>Measurement Principle</u>	<u>Energy Transducer</u>
Infrared absorption	Gases	Absorption of IR energy	Thermistors, thermopiles, capacitor microphones
Ultraviolet absorption	Gases	Absorption of UV energy	Phototubes
Light scattering	Aerosols	Scattering of visible light	Phototubes
Reflectance	Filtered particulates	Visible light reflectance	Phototubes
Ionization	Hydrocarbons	Ionization current measurement	Ionization chamber
Colorimetry	Reactive gases	Absorption of visible or near UV energy by colored compound	Barrier layer cells, photocubes
Conductometry	Acid gases	Electric conductivity	Conductivity cell
Coulometry	Electroreducible & oxidizable gases	Electrical current measurement	Coulometric or galvanic cell
Fluorescence	Fluorescible materials	Emission of UV or near UV energy	Phototubes
Nuclear activation	Particulates all elements	Conversion of stable isotope elements to radioactive isotopes by neutron & gamma photo-nuclear activation	Nuclear radiation detector

Adapted from Stern, Air Pollution, Vol. II, p. 430
Academic Press, N. Y. (1968)

measure the surface chemistry of these particles. One of the difficulties in sampling the cloud is that the concentration fluctuations throughout the cloud depend largely on the degree of mixing which occurs in the cloud. Conditions which promote rapid dispersion of the pollutants tend to cause large variation of the concentration, particularly near the source of pollutants, i. e. at the initial formation of the cloud. As time progresses, mixing rates decrease and the real concentration of the pollutant becomes more nearly uniform.

Since sampling of the cloud requires the utilization of aircraft for a platform for the instruments, probe velocity can dramatically affect the measured concentration. This is particularly true in sampling particulates and aerosols. True concentration would require isokinetic sampling which is difficult at the speeds of the aircraft. For particulates and aerosols, therefore, the relationship between the measured concentration of particles of any diameter to the true concentration for each probe velocity needs to be determined.

In addition to the requirement that the concentration of HC1 and other pollutants be determined by sampling, more precise measurement of cloud size as a function of time is required to permit direct comparison of measured concentration versus calculated concentrations.

8.2 STATE-OF-THE-ART

Table XVIII is a summary of the instrument capabilities of monitoring instruments presently utilized by NASA for insitu ground level measurements of the exhaust from Titan IIIC launch vehicles (ref. 11).

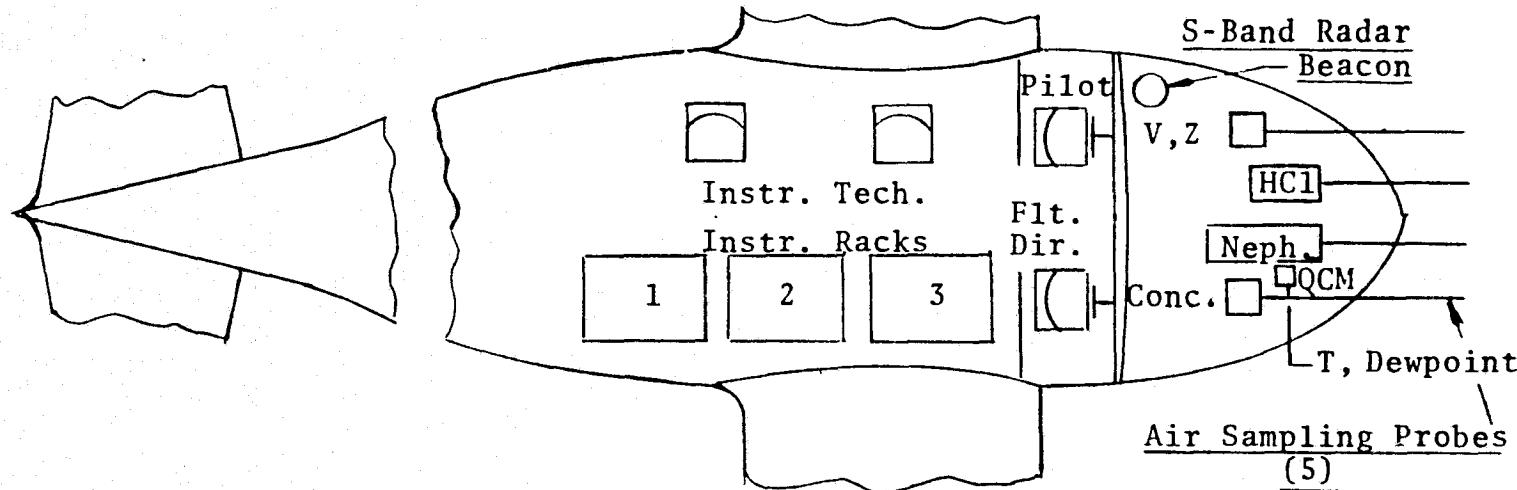
Figure 8.1 shows the specially instrumented twin engine aircraft used to penetrate the cloud following launch to measure gaseous constituents and particulates within the cloud (ref. 2).

The instruments presently being employed by NASA permits ground level measurements of HC1, CO₂ and particulates as well as in cloud measurements of CO, CO₂, NO, NO₂, HC1 and particles. These measurements of the HC1 will permit determination of the success of neutralization program and additional instrumentation will be required to measure the concentration of neutralizing agent and products of neutralization in the cloud. Measurements of the concentration of the neutralizing agent and/or products of neutralization are

T A B L E X V I I I
Instrument Capabilities

<u>Instrument/Species</u>	<u>Range</u>	<u>Detection Limit</u>	<u>Response to 90% Reading</u>	<u>Required Analysis</u>
Chemiluminescent detector/HCl (ref. 12)	0.05 - 50 ppmv	0.05 ppmv	1 - 5 sec	None
Microcoulometer HCl (ref. 13)	0.1 - 20 ppmv	0.1 ppmv	1 - 5 sec	None
Bubbler/HCl (ref. 14)	Greater than 50 ppmv-sec	50 ppmv-sec	Not applicable	Coulometric
pH paper/HCl (ref. 14)	Qualitative	1 ppmv	Not applicable	None
Infrared gas ^a analyzer CO ₂	1 - 50 ppmv above ambient	1 ppmv above amb.	2.5 sec	None
Mass monitor particles (ref. 14)	0.1 < dia. < 10 μm	10 $\mu\text{g}/\text{m}^3$	Less than 5 sec	None
Andersen/particles (ref. 14)	0.43 < dia. < 11 μm	50 μg	Not applicable	Gravimetric, neutron activation
Nuclepore filter particles (ref. 14)	Dia. greater than 0.01 μm	10 μg	Not applicable	Gravimetric, neutron activation
High volume sampler/ particles (ref. 14)	Dia. greater than 0.01 μm	200 μg	Not applicable	Gravimetric

^aInstrument specifications based on manufacturer's data.



TWIN ENGINE AIRCRAFT
CESSNA 402B

Speed: 100 to 230 knots
 Altitude: Up to 26,000 feet
 Range: 1,000 miles
 Duration: 5 hours

1. Flight Data
 T , Dewpoint
 V , Z , θ , t
 Data Acquisition
2. Gas Sampling Instru.
 CO/CO_2 Analyzer (Wilks)
 NO/NO_2 Analyzer
 (Monitor Lab)
 HC_1 Controls/Readout
 (Geomet)
3. Particle Sampling Instrumentation
 QCM (Celesco)
 $Nephelometer$ (MRI)
 $Concentrator$ (ERC)
 Andersen } Controls/Readout

Langley Atmospheric Sampling Aircraft - Launch Effluent Configuration

FIGURE 8.1

required to determine the degree of mixing of the neutralizing agent in the cloud.

8.3 BASIC AND APPLIED RESEARCH NEEDED

In addition to the present instrumentation being utilized by NASA to measure the concentration of several of the effluents of solid rocket launches, additional instrumentation is required to sample the cloud for the neutralizing agents and products of neutralization. Instruments are needed which will measure the physical and chemical properties of particles to better understand the interactions between gaseous and particulate effluents from the rocket launch.

Lasers have been used successfully for detecting aerosols and particulate matter in clouds, smoke stack plumes and inversion layers (ref. 15). However, a great deal of basic and applied research is needed to develop tuneable lasers with wide enough range of tuning, sufficient power and small spectral width for identifying the chemical composition of pollutants *insitu* by resonant adsorption.

9. EFFECTS OF NEUTRALIZATION

Neutralization of the HCl in the rocket effluent is successful only if the introduction of the neutralizing agent and products of neutralization are not harmful to the environment. Without neutralization, the HCl may result in acid rain if meteorological conditions are right. There is increasing concern in this country on acid rain. Measurements of the pH of rain in north central Florida was 5.2 to 6.8 during 1967-68 (ref. 16). This compares to a summer average of 3.81 at New Haven, Connecticut during 1970. The effects of HCl pollution on plant and animal life is noted in Section 4 of the report.

The effects on the environment from the neutralizing agents and products of neutralization are for the most part unknown. Smith reports (ref. 17) on the effects of air pollution on temperate forest but gives only general comments with no specific reference to any particular gaseous or particulate pollutant. Table XIX from Ryder (ref. 18) lists variations in sensitivity of certain plants to selective pollutants. Similar data are reported on other plants but the effect of materials such as ammonia, ammonium salts and sodium salts is difficult to find. Some investigators (ref. 19) indicate that ammonia has a pronounced detrimental effect on plants which resembles that of HCl.

Salts of sodium chloride yield a positive ion of sodium and a negative ion of chloride. The chloride ion is of very little environmental consequence but the sodium ion, because it is more reactive, has the advantage when competing for the positive ion adsorption sites and tends to displace the calcium ion which is required for vegetation. Excess sodium and chloride ions can have a toxic effect on plant tissue, resulting in leaf discoloration for chloride and a deeper leaf color and premature shedding of leaves from excess sodium ions (ref. 20). The growth of most plants is retarded when the salt content of the soil exceeds a rather low value. Some species are more sensitive to high concentrations of chloride and are affected by salt concentration, not soil condition (ref. 21). The resistance of different species to salinity cannot depend only on salinity of water used, but on all affecting conditions, like chemical and physical structure of soil and the climate environmental factors. In the utilization of saline irrigation for agriculture, it was found that for citrus, the use of slightly brackish water (1.5 to 3%) gave excellent yield and as long as the salinity of the water did not exceed 3.3%; it is actually essential for getting the largest and best yield of tomato, eggplant, pepper,

TABLE XIX

Crop, Ornamental and Forest Species in Which Variation
in Sensitivity to the Pollutants Named has been Observed

<u>SPECIES</u>	<u>POLLUTANT</u>	<u>REFERENCE</u>
Crop Species		
Alfalfa (<i>medicago sativa</i> L.)	Ozone	19
Citrus (<i>Citrus</i> sp)	Fluoride	20
Cucumber (<i>Cucumis Sativus</i> L.)	Ozone	21
Grain sorghum (<i>Sorghum vulgare</i> Pers.)	Fluoride	22
Green bean (<i>Phaseolus vulgaris</i> L.)	Ozone, amb. air	23
Lettuce (<i>Lactuca sativa</i> L.)	Ozone	18
Oats (<i>Arena sativa</i> L.)	Ozone	24
Onion (<i>Allium cepa</i> L.)	Ozone	3
Potato (<i>Solanum tuberosum</i> L.)	Ozone	24
Radish (<i>Raphanus sativus</i> L.)	Ozone	25
Red clover (<i>Trifolium pratense</i> L.)	Ozone	26
Spinach (<i>Spinacia oleracea</i> L.)	Oxidant	14
Sweet corn (<i>Zea mays</i> L.)	Oxidant	27
Tobacco (<i>Nicotiana tabacum</i> L.)	Ozone	28
Tomato (<i>Lycopersicon esculentum</i> Mill.)	Ozone	25
Turfgrass (Several species)	Ozone, SO ₂	29
White bean (<i>Phaseolus vulgaris</i> L.)	Oxidant	6
Ornamental Species		
Coleus (<i>Coleus</i> sp.)	Ozone	21
Gladiolus (<i>Gladiolus</i> sp.)	Fluoride	30
Petunia (<i>Petunia hybrida</i> Vilm.)	Ozone, PAN, SO ₂ , NO ₂ , irrad exhaust	7
Forest Species		
Douglas fir (<i>Pseudotsuga taxifolia</i> Brit.)	SO ₂	31
Eastern white pine (<i>Pinus strobus</i> L.)	Ozone, SO ₂	32
Larch (<i>Larix</i> sp.)	SO ₂	33
Lodgepole pine (<i>Pinus contorta</i> Dougl.)	SO ₂	31
Norway spruce (<i>Picea abies</i> L.)	SO ₂ , fluoride	34
Ponderosa pine (<i>Pinus ponderosa</i> Laws)	Oxidant, fluoride	35
Scotch pine (<i>Pinus sylvestris</i> L.)	SO ₂ , fluoride	34

cabbage, fennel, asparagus and artichoke (ref. 22). Ten thousand ppm or more of chloride has been found in apparently normal leaves. Since ammonia and HCl have similar toxicity to plant life the effect may be due to acidity and alkalinity, uncomplicated by other toxic properties (ref. 23).

Unlike excess sodium and chloride, plants require nitrogen which is obtained from ammonium ions. Ammonium chloride, therefore, is used in fertilizers. The deposition of the ammonium chloride salts on the environment should have no toxic effects on the plant life and may provide additional nutrients.

In general, the available information on the effect of air pollutants on plant and animal life is limited. Although a considerable amount of investigation has been made on plants of sulfur dioxide, hydrogen fluoride and smog (Table XX, ref. 24), little or no experimental work on the effects of the neutralizing agents and their products of neutralization is available. Generally, the neutralizing agents proposed and the products of neutralization are not encountered in normal air pollution investigations. To ascertain the possible effects on the environment, experimental work for the specific agent used needs to be carried out.

T A B L E X X

Relative Susceptibility of a Few Plants to Injury by Sulfur Dioxide, Hydrogen Fluoride and Smog

<u>Agent</u>	<u>Sensitive</u>	<u>Intermediate</u>	<u>Resistant</u>
SO ₂	Alfalfa	Dandelion	Gladiolus
	Barley	Cabbage	Corn
	Endive	Apricot	Grapes
	Cotton	Peach	
	Gladiolus	Prune	
	Sweet pea	Gladiolus	
	Rhubarb		
	Radish		
	Spinach		
	Lettuce, head		
	Sweet potato		
	Broccoli		
	Squash		
	Table beet		
	Oats		
	Buckwheat		
	Clover		

TABLE XX (Continued)

<u>Agent</u>	<u>Sensitive</u>	<u>Intermediate</u>	<u>Resistant</u>
SO ₂	Carrot Wheat Larch		
HF.....	Gladiolus Apricot Prune Larch Sweet potato (some varieties) Corn Grapes (some European varieties) Peach Buckwheat	Alfalfa Barley Buckwheat Carrot Clover Lettuce, head Oats Rhubarb Spinach Sweet potato (some var.) Wheat	Cabbage Cotton Dandelion Squash Sweet pea
Smog.....	Endive Spinach Romaine lettuce Barley (young) Alfalfa Table beet Oats Buckwheat	Dandelion Lettuce, head Radish Squash Sweet pea	Broccoli Cabbage Carrot Corn Gladiolus Rhubarb Squash Wheat

10. TEST PROGRAM

10.1 DEFINITION OF THE PROBLEM

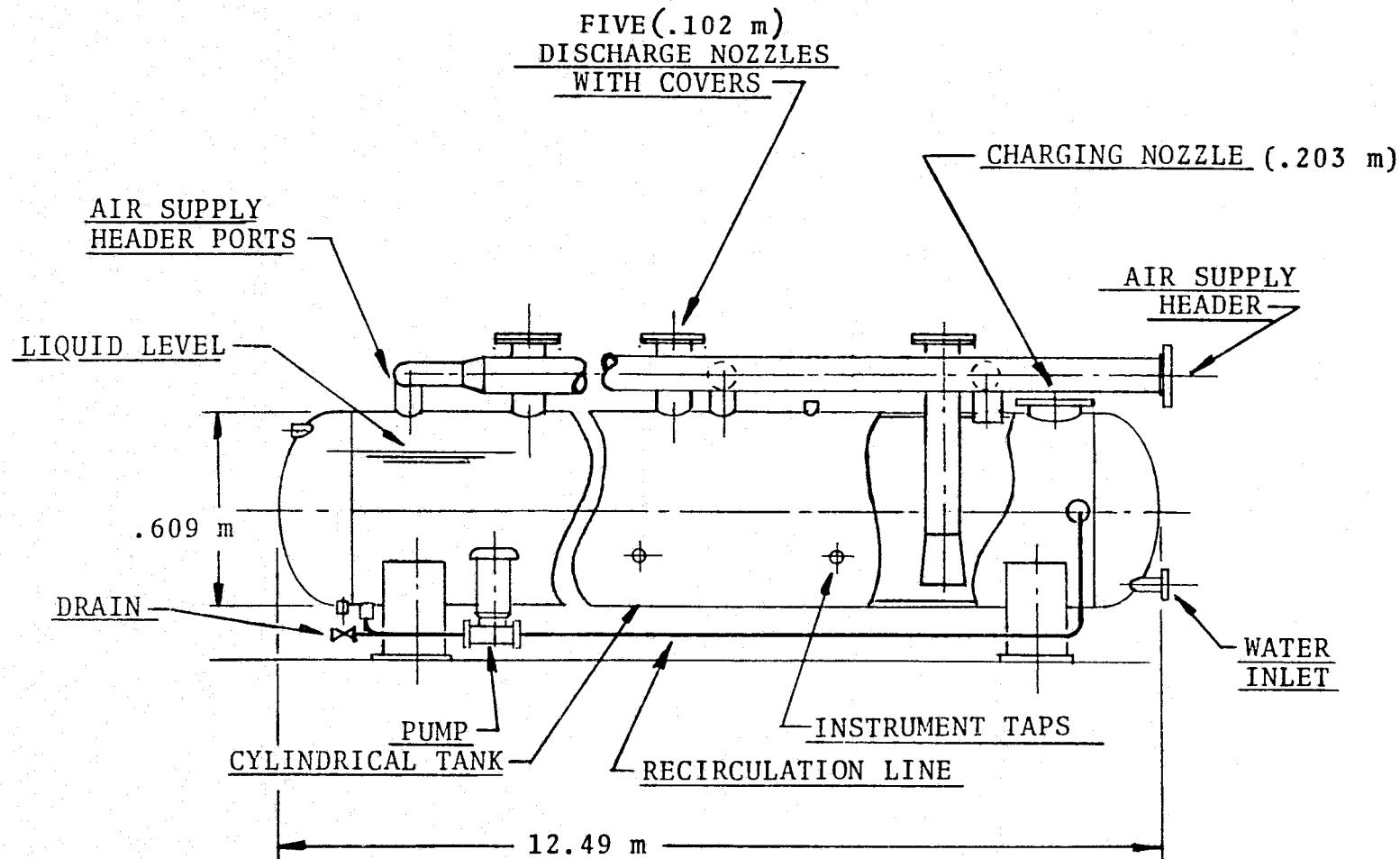
This study was initiated after it had been postulated that the launch of the space shuttle might lead to an environmental pollution problem. At this time it is not really known how large and/or severe the problem will be. In order to verify some aspects of this problem relevant to the proposed solution, it appears useful to start an intensive program of sampling the clouds formed during the launch of vehicles emitting hydrogen chloride into the atmosphere. The most likely space program to be used for this purpose appears to be the Delta launches. They are fairly frequent and the scale of these launches is approximately one-thirtieth of that of the space shuttle with regard to hydrogen chloride emission.

The test program initially should primarily be a sampling and mapping program with the following objectives:

- a) Determine whether ground cloud and column cloud do or do not mix.
- b) Determine the concentration of hydrogen chloride in ground and column clouds as a function of time and weather conditions.
- c) Determine the size and shape of the ground and column clouds as a function of time and weather conditions.

10.2 DELIVERY OF NEUTRALIZING AGENT FROM A GROUND-INSTALLED SYSTEM

The Delta launches appear to be suited for a program of injecting the neutralizing agent into the ground cloud. Scale of the test equipment will be approximately one-thirtieth of that for the space shuttles. Figure 10.1 shows a delivery tank satisfactory for the Delta launch complex. The tank is quite small and it should be possible to move the tank about for variation of the injection point into the ground cloud.



Na_2CO_3 Storage & Delivery Tank for Delta Test

FIGURE 10.1

10.3 DELIVERY OF NEUTRALIZING AGENT INTO THE COLUMN CLOUD

A single helicopter of the Chinook type will be satisfactory to carry all of the required neutralizing agent.

10.4 ESTIMATED COST OF EQUIPMENT FOR THE TEST PROGRAM

It is assumed that both ground and airborne equipment will be shop-fabricated items. Cost of these systems is \$15,800.00 and \$13,000.00, respectively.

11. RECOMMENDATIONS

11.1 DELIVERY OF NEUTRALIZING AGENTS

The study shows clearly that the delivery of neutralizing agent into the ground cloud should be carried out during the formation of the cloud with equipment located on the ground. Delivery rates need to be such that all of the required neutralizing agent is injected in a period of 10 sec.

To make equipment reasonably small, tanks containing the neutralizing agent should be located in the area over which the exhaust gases from the rocket flow. Then pipe sizes of the delivery system will be small, startup of flow of solution is rapid and cutoff, in case of launch abort, can be reasonably achieved.

Because of short delivery time a concentrated solution of sodium carbonate should be used as the neutralizing agent. The advantages of this solution are:

- a) Low pressure, safe storage for indefinite periods of time.
- b) Nontoxic vapors.
- c) Cost of solution per launch is reasonable.
- d) Lowest cost nontoxic ground-installed delivery system.

The delivery of neutralizing agent to the column cloud needs to be carried out by aircraft as soon as is possible after the launch. The preferred aircraft is the Sikorsky CH-54B helicopter which can pick up a tank and carry it externally to its fuselage. The only feasible neutralizing agent to be used for delivery by aircraft is ammonia. The ammonia will be stored in the tank at high pressure and ambient temperature and will be discharged from the tank without need for an external pressurization system. The dispersion of ammonia in the column cloud will be reasonably good because the liquid expanded to atmospheric pressure will separate into a fog. This fog will contain approximately 72% liquid and 28% vapor. The liquid will exist as very small particles. Difference in density between the ammonia cloud and the column cloud will provide relative motion. As a result, a single pass through the cloud by a helicopter flying at a low speed of 60-80 km/hr will cover a large volume of the cloud.

11.2 MODELING

Before fully implementing the system for the space shuttle program, modeling at a reduced scale should be carried out. The discussion of Section 10 indicates that the Delta vehicle provides a good test system for evaluation of the cloud neutralization system. The ground based equipment is small, is shop fabricated and can be moved about the Delta launch facility without much difficulty.

An airborne delivery system for injection of ammonia into the column cloud can be carried by almost any helicopter. The total amount of ammonia to be carried is of the order of 600 kg. Total weight of tank, nozzles, liquid, etc. will be of the order of 1,000 kg.

11.3 SAMPLING

It is essential that the hypothesis of two separate clouds is verified. This could be done by injecting a tracer in the ground cloud during its formation and analyzing the cloud(s) for a period of 1/2 to 1 hr after launch. The analysis of the contents of the cloud should preferably be carried out with a slow speed aircraft. This would make it possible to "map" the cloud more closely.

11.4 SIZE OF CLOUD

It appears useful to provide a correlation between the cloud volume and concentration of hydrogen chloride as a function of time. This is particularly true for the column cloud since this cloud can only be neutralized by airborne equipment.

11.5 DATA CORRELATION

It appears useful to provide a correlation between weather conditions during the launch and the formation and final shape of the cloud. Wind velocity and direction as a function of altitude is expected to influence the size of the final cloud and its concentration of hydrogen chloride measured in ppm greatly. Plots of the type shown in Figure 3.1 will be quite useful in predicting the potential effects of washout on the surrounding territory.

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